


The microstratigraphic record of human activities and formation processes at the Mesolithic shell midden of Poças de São Bento (Sado Valley, Portugal)

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Abstract Shell midden formation is largely controlled by anthropogenic processes, resulting from human exploitation of aquatic resources. This makes shell middens archives of both human behaviour and palaeoenvironmental records. However, their often complex stratigraphy hampers the isolation of individual anthropogenic events. In the central/southern coast of Portugal, extensive inland estuaries were preferential settings for Mesolithic groups from c. 6200 cal BC. Here, we present a microstratigraphic approach to the shell midden of Poças de São Bento, one of the largest and best-known sites in the Sado Valley. The microfacies approach was based on sedimentary components, their abundance and arrangement, and post-depositional processes. Anthropogenic processes identified as tossing events and anthropogenically reworked deposits allowed inferences on spatial organisation, preferential refuse areas, occupational surfaces, and temporality of the occupations. The presence of calcareous pebbles in the anthropogenic, shell-rich sediments, together with foraminifera, presumably from the estuarine marshes, is compared with the regional geology, providing a hypothetical location of

the shellfish gathering. The microstratigraphy described reveals a full internal dynamic in the formation of the apparently homogeneous shell midden layer. The human activities inferred at Poças de São Bento have many similarities with those reported for Cabeço da Amoreira in the nearby Tagus palaeo-estuary. This evidence points to the need for further micro-morphological approaches in similar deposits. The study of shell midden formation processes, through integrative microcontextual approaches, plays a major role in understanding Mesolithic societies in the large early Holocene estuary environments of Atlantic Iberia.

Keywords Mesolithic · Shell middens · Sado Valley · Micromorphology · Human activities · Formation processes

Introduction

Shell middens are particularly interesting archaeological deposits because of their largely anthropogenic nature, directly resulting from human activities, which makes them sedimentary deposits that can be considered artefacts in themselves. The study of such contexts, however, faces several difficulties in the reconstruction of the human-driven formation processes. Shell-rich deposits might present macroscopically an apparent sedimentary homogeneity that in the field hampers the isolation of the individual events involved in the accretion of these types of deposits (Stein 1992; Gutiérrez-Zugasti et al. 2011). J. Roche (1966) noted in the Muge shell middens in Portugal that individualised occupations relatively independent from each other might generate continuous stratigraphic sequences, together with the artefacts embedded in those sediments. This has serious implications in archaeological interpretation due to unnoticed mixing of

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materials from different events. Such an intricate stratigraphic record also makes shell midden deposits archives of detailed information about both human behaviour and the palaeo-ecological conditions they exploited. Seasonality patterns are one of the aspects of human behaviour that have recently been extracted from shell mound deposits (see e.g. Surge et al. 2013; Colonese et al. 2009, 2012), as they enable season of shellfish gathering to be determined through oxygen isotopic analysis of shell growth lines. At the regional scale, shell middens have also been explored as palaeoenvironmental proxies. Their location has been used for mapping changes in Holocene coastal environments (Villagran and Giannini 2014) and isotope and elemental analysis of shell growth lines have also been used for palaeoclimate reconstructions, namely sea surface temperature variations (Gutiérrez-Zugasti et al. 2015). Both aspects of shell middens potential for archaeological interpretations (human behaviour and palaeoenvironment) are enhanced by the fact that this type of deposit is known in coastal areas worldwide in different chronologies (Álvarez et al. 2011; Balbo et al. 2011).

In southwestern Iberia, in particular, intensive shellfish exploitation during the Mesolithic led to the accumulation of shell middens, generally associated with adaptations to the changing environment in the early Holocene (Gutiérrez-Zugasti et al. 2011). Sea level rise caused the formation of extensive inland estuaries (Dias et al. 2000), such as those of the Tagus and Sado Rivers, that were preferential settings for the Mesolithic groups from the late seventh millennium cal BC (Bicho et al. 2010; Diniz and Arias 2012; Peyroteo Stjerna 2016).

Here, we present a microstratigraphic approach based on micromorphological analysis of the shell midden of Poças de São Bento, one of the largest of the 12 Mesolithic shell midden sites in the Sado Valley. The shell midden layer is not continuous, however, which has been interpreted as the result of mainly lateral accretion of shell-rich deposits (rather than superposition) by semi-sedentary occupations, resulting in a laterally discontinuous shell midden layer (Diniz and Arias 2012; Arnaud 2000; Larsson 1996). Through micromorphological analysis, we aimed to recognise single events of human activities involved in shell midden formation. Our approach also sought to make a spatial correlation between different sampled areas of the site, in order to identify any sedimentological differences between spatially disconnected shell midden accumulations, eventually associated with different function. Furthermore, we wished to clarify if there are any gaps in sedimentation related to absence of occupation. It was also our concern to address the diagenetic processes that the shell midden underwent, in order to provide an integrative assessment, at high resolution, of preservation

conditions of the human-derived deposits and the artefacts in them.

Poças de São Bento in its geological and archaeological context

Poças de São Bento is an open-air site on a gentle slope, limited to the SE by a brook belonging to a small subsidiary basin of the Sado River (Fig. 1). Nowadays, the site is 3 km south of Sado, on a Cenozoic platform, at an altitude of c. 80 m above present mean sea level. The Sado Basin is incised into this platform exposing successive layers of Miocene conglomerates and sandstones in quite steep slopes. The platform is covered by a Pleistocene/Holocene aeolian sand cover, on which the shell midden rests. The location of Poças de São Bento is substantially further inland, when compared to the other sites, which tend to follow a somewhat consistent location pattern close to the erosion edge of the platform, usually with good overview of the Sado alluvial plain. Several shell midden sites are currently known in both margins of the Sado, Arapouco being the furthest downstream (Fig. 1). Poças de São Bento is one of the two largest sites, with an area of c. 3500 m², only exceeded by Cabeço do Pez, the furthest upstream shell midden known, with an area of ~4000 m². The alluvial plain is characterised, today, by extensive rice fields, and the Vale dos Açudes stream is controlled by a system of dams and largely modified by recent agricultural activities that make it extremely difficult to visualise the natural course of the hydrographic basin.

The existence of estuarine marshland environments upstream of Arapouco during the Mesolithic is an open question and currently the object of on-going investigations. Preliminary data based on sediment cores from the Sado valley infill suggest that there was marine influence near Arapouco (located ~20 km from the present-day estuary), between c. 1650 and 1400 cal BC, when mean sea level was similar to the present (Costa et al. 2015, 2017). However, there is not yet sufficient data to characterise the environment in the shell middens area at 6000 cal BC, when, according to sea level curves proposed for the Portuguese coast, mean sea level was c. 10 m below the present level (Dias 2000).

The discovery of this cluster of shell middens with necropolises in the 1930s motivated extensive excavation programmes during the 1950s and 1960s by M. Heleno. A later project directed by J. Arnaud and L. Larsson, in the 1980s, carried out systematic excavations, sampling and study of artefactual collections (Arnaud 1989, 2000; Larsson 1996, 2010). Since 2010, a collaborative project between the University of Cantabria (Santander, Spain) and the University of Lisbon (Portugal) has resumed the excavations at Poças de São Bento, as well as in other sites in the Sado Valley (Arias et al. 2015; Diniz and Arias 2012).

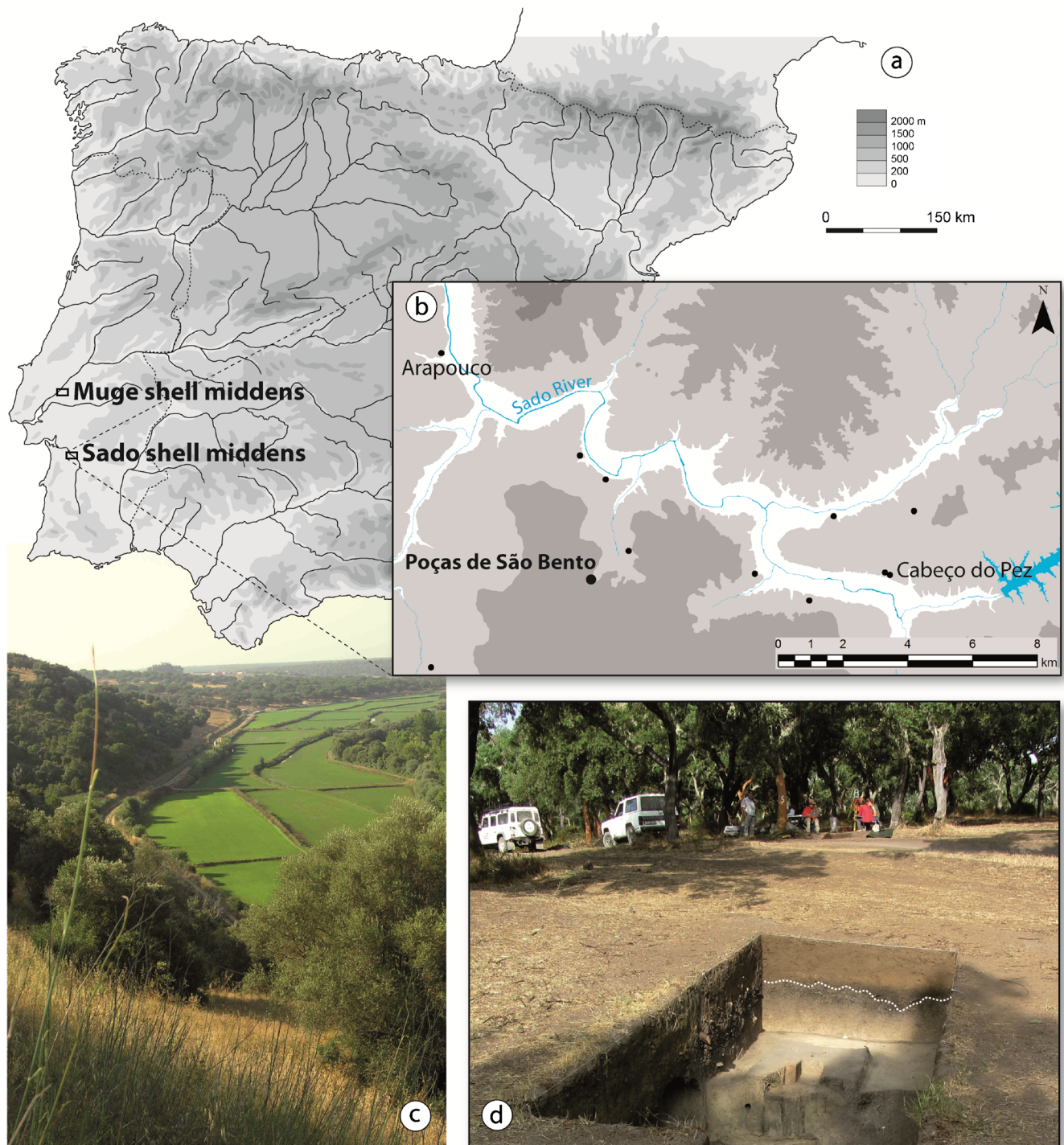


Fig. 1 Location and surroundings of Poças de São Bento. **a** Geographical location of the Sado and Muge shell middens in the Iberian Peninsula. **b** Close-up of the Sado Valley with location of Poças de São Bento, the sites mentioned in the text of Arapouco and Cabeço do Pez, and the other known shell midden sites (*black dots*); note that Poças de São Bento is a considerable distance from the Sado in comparison with

the other sites. **c** View of the Sado alluvial plain, now extensive rice fields, from a typical location of most shell middens, close to the edge of the erosion platform; note the steepness of the slopes. **d** General view of the site of Poças de São Bento, with Area 9 in the foreground, from the NE (see Fig. 2), during the 2015 excavation; the surface of the shell midden layer here is indicated by the *dashed line in the front section*

Previous publications on Poças de São Bento have focused mainly on its artefactual assemblages, namely lithic technology (Araújo 1995–1997; Araújo et al. 2015), raw material provenance (Pimentel et al. 2015), funerary practices

(Stjerna 2015), human dietary reconstructions (Umbelino et al. 2007; Fontanals-Coll et al. 2014; Peyroteo Stjerna 2016) and macrobotanical, non-woody remains (López-Dóriga et al. 2016).

Stratigraphic and chronological framework

At Poças de São Bento shell midden, the stratigraphy is quite uniform in all excavated areas and test pits carried out by the current archaeological project, with some variations, mainly concerning the thickness and density of shells in the deposits. Arias et al. (2015) classified the overall site stratigraphy in phases, combining the previous and new radiometric dates with macroscopic observations in the field, as summarised in Table 1.

The shell midden deposits rest on a cover of Pleistocene/Holocene aeolian sand. These sands are fairly homogeneous clast-supported and weakly compacted, except for the occurrence of post-depositional calcareous concretions related to root activity (Fig. 2c). An OSL age for Phase A sediments, in Area 9, associates the stabilisation and burial of these basal sands slightly prior to the beginning of the Holocene (Table 1).

The set of ^{14}C dates (Table 1) suggest that the earliest occupation at Poças de São Bento is that of Phase B, which corresponds to the shell midden layers, dated to between the late seventh millennium cal BC, and the sixth millennium cal BC. Broadly speaking, the shell midden deposits exhibit a greyish colour and a maximum thickness of around 80 cm and are sedimentologically quite homogeneous, loose sands with highly fragmented shells. These sediments enclose loosely packed centimetric pebbles of allochthonous origin—some of them used as lithic raw material (see Table 2)—as well as lithics and bones, usually poorly preserved due to weathering and bioturbation. Spatially, however, each of the archaeological accumulations is quite sparse, with common lateral discontinuities, which result in patchy accumulations with gradual contacts with the under and overlying sediments; they are difficult to individualise topographically. Some sedimentological stratification within the shell midden layer is visible only in deposits in Areas 9 and 11 (Fig. 2). Here, the archaeological deposits present some internal stratification, with centimetre-thick lenses with sharp contacts, predominantly formed by quite complete shell valves.

In terms of habitat features, hearths and putative post-holes have been reported at the site (Arnaud 1989, 2000; Larsson 1996). Some negative structures, or pits, were identified dug into the Pleistocene/Holocene basal sands, usually under a layer of shell-rich Phase B sediments; the infilling seems to be sedimentologically equivalent to the same Phase B sediments (Fig. 2c). In Area 1, these sediments included a dog burial (Arias et al. 2015). The human burials so far identified at Poças de São Bento were found in the basal sands below the lower contacts of the shell midden layer. They are concentrated in an area of the site's estimated perimeter extensively excavated in former projects (Fig. 2).

Overlying the shell midden layers are the greasy, dark sediments of Phase C, which post-date the Mesolithic, a pedological horizon affecting the upper part of shell-rich sediments (Fig. 2). The stratigraphic units corresponding to Phase C exhibit intense post-depositional bioturbation and admixture of pedogenic and anthropogenic materials. The radiocarbon result from Phase C sediments in Area 6, from a sample of total organic matter of sediment, revealed an early fifth millennium cal BC chronology, coherent with the scarce Neolithic pottery sherds dispersed in this layer (Arias et al. 2015). Finally, the uppermost sediments, Phase D, have a sharp lower contact with Phase C sediments and correspond to the present-day soil surface.

Materials and methods

In geoarchaeology, micromorphology refers to the microscopic study of undisturbed and oriented blocks of artificially consolidated “soils, sediments, and archaeological features and materials in thin section” (Goldberg and Aldeias 2016). This technique allows the observation of the cultural remains in their surrounding sedimentary matrix, preserving the contextual arrangement of the deposits (Courty et al. 1989; Goldberg and Berna 2010). In archaeological contexts, micromorphology has proven to be especially useful for several relevant aspects of the archaeological record interpretation, such as the distinction between anthropogenic and natural processes (Aldeias et al. 2014; Mallol et al. 2010; Goldberg et al. 2003; Karkanas 2002), including the nature and significance of stratigraphic contacts and discontinuities (Mallol and Mentzer 2015). It has been particularly successful in the identification and assessment of the degree of preservation of anthropogenic features, such as combustion features (Mentzer 2014; Aldeias et al. 2012) and occupational surfaces—including Mesolithic ones (Zerboni 2011)—and the recognition of human activities such as bedding, trampling (Goldberg et al. 2009; Miller et al. 2013) or intentional reworking of debris (Shillito et al. 2011; Sherwood and Kidder 2011). These types of activities are very often only discernible at this microscopic scale.

The concept of microfacies has been used to synthesise deposits that share a set of specific microscopic attributes in thin section (Courty 2001; Flügel 2004). The subsequent interpretation of those attributes, a combination of sedimentary components, their spatial organisation and geometry, or other parameters, when consistently isolated from adjacent deposits, is interpreted as the result of a certain process, natural or anthropogenic. In archaeological sediments, different microfacies types might be recurrently in close association (e.g. Goldberg et al. 2009).

Table 1 Summary of the chronological phases identified at Poças de São Bento and absolute chronology

| Phase and field description after Arias et al. (2015) | Absolute dates (OSL date in italics, radiocarbon dates in plain text) | | | Stratigraphic unit (context of dated samples) | |
|--|---|----------------------------------|---------------|---|------------------------------------|
| | Reference | Material | Result | cal BC (95.4% probability) | |
| Geologic substrate: Cenozoic ferruginous reddish or yellowish sandstone and Pleistocene/Holocene sands. | — | — | — | — | — |
| A Greyish sands with a low density of shells and lithics. | GL14060 | — | 12 ± 1 ka | 12,000–8000 | 912 (Area 9) |
| B Dense accumulation of mollusc shells (mainly <i>Scrobicularia plana</i> and in a smaller proportion, <i>Cerastoderma edule</i>) in a sandy sediment with a low density of other kinds of archaeological materials. | OxA-29,113 | <i>Homo sapiens</i> bone | 7238 ± 35 | 6211–6031 | 613 (Area 6) |
| | Lu-2769 (Larsson 2010) | Shells | 7150 ± 70 | 6006–5653/ 5923–5281 | 45–50 cm (former projects) |
| | OxA-29,114 | <i>Scrobicularia plana</i> shell | 7121 ± 35 BP | 5960–5666/ 5874–5275 | 403 (Area 5) |
| | OxA-24,652 | <i>Cerastoderma edule</i> shell | 7107 ± 37 BP | 5951–5653/ 5861–5256 | 3/7 (Area 1) |
| | OxA-24,648 | <i>C. edule</i> shell | 7084 ± 36 BP | 5917–5627/ 5830–5225 | |
| | OxA-24,650(<i>C. edule</i> shell) | <i>C. edule</i> shell | 7070 ± 35 BP | 5901–5620/ 5817–5212 | |
| | OxA-24,651 | <i>C. edule</i> shell | 7053 ± 37 BP | 5890–5610/ 5806–5200 | |
| | OxA-24,649 | <i>C. edule</i> shell | 7052 ± 35 BP | 5886–5611/ 5804–5200 | |
| | Lu-2770 (Larsson 2010) | Shells | 7050 ± 60 BP | 5921–5582/ 5831–5186 | 65–70 cm (former projects) |
| | Q-2493 (Arnaud 1989) | Shells | 7040 ± 70 BP | 5921–5556/ 5829–5160 | Lower layer (3) (former projects) |
| C Blackish sand with some allocthonous sandstone blocks, a low density of shells and sparse archaeological material, including lithics, bones and scarce Neolithic pottery sherds. It corresponds to the upper horizon of an A horizon of a palaeosol. | OxA-29,235 | <i>Meles meles</i> bone | 6962 ± 37 BP | 5974–5744 | 3/7 (Area 1) |
| | Q-2494(Arnaud 1989) | Shells | 6780 ± 65 BP | 5807–5561 | Middle layer (2) (former projects) |
| | Q-2495(Arnaud 1989) | Shells | 6850 ± 70 BP | 5724–5393/ 5622–4930 | |
| | OxA-26,094 | <i>Canis familiaris</i> bone | 6866 ± 33 BP | 5837–5672 | 8 (dog burial—Area 1) |
| | Ua-425(Larsson 2010) | <i>H. sapiens</i> bone | 5390 ± 110 BP | 4448–3984 | Burial 11 (former projects) |
| | OxA-29,170 | Organic sediment | 5511 ± 34 BP | 5048–4840 | 603 (Area 6) |
| | OxA-29,169 | Organic sediment | 6045 ± 39 BP | 4453–4344 | |
| | — | — | — | — | — |
| | — | — | — | — | — |
| | — | — | — | — | — |
| D Yellowish sand with a low density of archaeological remains, including some modern pottery. | — | — | — | — | — |
| Surface: Modern soil. | — | — | — | — | — |

For information about the contexts, see Fig. 2. OSL date is in italics, ¹⁴C dates in plain text. The dates were obtained by the project currently investigating the Sado shell middens (P.I. PA and MD), except those for which the original publication reference is indicated. ¹⁴C calibrations are as reported in Table 1 in López-Dóriga (2016)

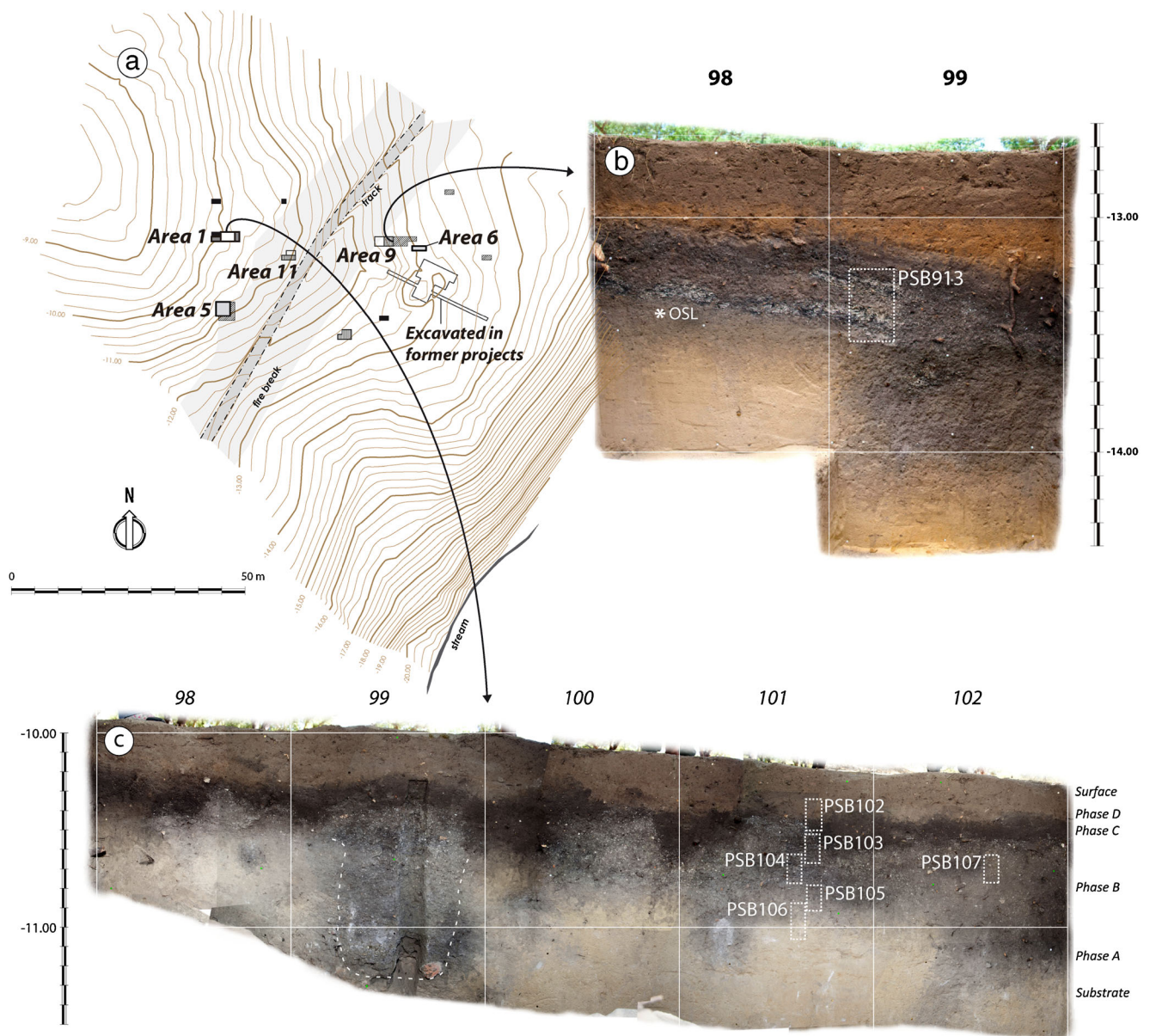


Fig. 2 The site of Poças de São Bento. **a** General site topography with indication of Areas mentioned in the text, 1, 5, 6, and 9, and other excavated areas. **b** Sampled profile in Area 9, with indication of the micromorphological block sample PSB913; note the oblique orientation, superposition and irregular upper contacts of the shell

midden layers. The OSL sampling location is also marked (OSL). **c** Sampled profile in Area 1 with chronological phases after Arias et al. (2015), with indication of the micromorphological block samples PSB102 to PSB107; note the homogeneity of the shell midden layer (Phase B) and the pit feature in square 99 (dashed line)

This approach helps to describe anthropogenic-derived millimetre-thick strata, which can be difficult to isolate in the field, and scale up their relation with the broader archaeological context. The microfacies approach can, therefore, contribute significantly to the reconstruction of formation process and human activities at a given site.

A microfacies approach has been successfully applied in shell mounds on the southern coast of Brazil (Villagran 2014b, Villagran et al. 2009) and in the ethnoarchaeological work at historical shell middens in Tierra del Fuego (Villagran et al. 2011; Balbo et al. 2010). Recently, this

approach allowed for the recognition of different types of deposits in primary and secondary positions, due to both natural and anthropogenic processes, as well as occupational surfaces, within the Cabeço da Amoreira shellmound (Aldeias and Bicho 2016), a site which is in the regional vicinity and roughly contemporaneous to the deposits of Poças de São Bento studied here.

The micromorphological samples presented here were collected in Areas 1, 5 and 9 (Fig. 2a), attending to specific stratigraphic features, highlighted below (see also Fig. 2b, c). The sampling consisted of carving out the

Table 2 Description and genetic interpretation of the main components observed in Poças de São Bento thin sections

| Component | Description | Genetic interpretation | Thin sections |
|------------------------------|---|---|--|
| Silt and sand mineral grains | Sand and silt sized mineral grains are the dominant component in all thin sections. Their composition consists of 80% quartz, 15% feldspar (microcline and other K-feldspars and fewer plagioclase) and 5% opaque minerals. Shapes vary from sub-angular to well-rounded. Very frequently, feldspars exhibit advanced alteration to secondary clay minerals. | The lithologies and general roundness of the grains reflect the Pleistocene/Holocene sand cover on which the shell midden rests, continuously reworked by human and natural processes and incorporated into the archaeological sediments. | All |
| Pebbles | Sub-rounded to rounded pebbles of quartz and rock-fragments, such as arkose, are ubiquitous in the shell midden related sediments, up to 1.5 cm in thin section and up to ~7 cm in the field. Rounded calcareous pebbles are common in specific shell-rich sediments and exhibit optical signs of having been exposed to high temperatures (calcination and thermal cracks). | The lithologies, which are absent in the Pleistocene/Holocene sand cover substrate, and their association with shell-midden sediments indicate transport to the site by humans (from elsewhere in the valley, where such materials outcrop), possibly as a by-product of shellfish gathering and other sediment-bearing activities. An intentional transport for knapping and structuration of combustion and other features is also a possibility. | 103.2, 104.1, 104.2, 105.1, 105.2; 107, 108, 913.1 |
| Mollusc shells | Shell fragments of peppery furrow (<i>Scrobicularia plana</i>) are dominant in all shell-rich sediments at Poças de São Bento. Cockle (<i>Cerastoderma edule</i>) shells are less frequent and less fragmented. Depending on the context, the degree of calcium depletion, fragmentation, orientation and organisation patterns are variable. | Anthropogenic input resulting from shellfish resources exploitation. | All, except 102 |
| Fishbones and mammal bones | Mammal bones fragments are extremely rare although existent in all thin sections and only in two instances exceed sand size. Fishbones, including vertebra are present in all thin sections of shell-rich sediments. Bones exhibit some physical weathering, occasional calcium carbonate mineralisation and rarer signs of burning (reddish colour). | Animal/fish processing and consumption by humans at the site. | 103.1, 103.2, 104.1, 104.2, 105.1, 105.2, 107, 108, 913.1, 913.2, 913.3, 913.4 |
| Wood charcoal | Well-preserved fragments from fine sand size up to 1 cm are abundant, particularly in shell-rich sediments. | Anthropogenic combustion activities. | All, except 106.1 and 106.2 |
| Clay | Very little clay was observed in the thin sections. In shell midden layers, it occurs mostly as small amounts of clay attached to shells or coarser sand grains, sometimes forming connecting bridges between those (chitonic/gefuric c/f related distributions). Also, very few, isolated aggregates were identified. Two different main compositions were distinguished in the shell midden layers: 1. Reddish brown, stipple speckled b-fabric, with organic matter inclusions. 2. Orange/yellow, crystallitic b-fabric, with silty mineral inclusions. Both types of clay aggregates occur in mF type 5a (interconnected shells) deposits (see below). | Origin uncertain, probably result of shell gathering in estuarine marshes, redeposited by post-depositional water percolation. | 913.1, 913.2, 913.3, 913.4 |
| Char | Char aggregates are present in shell-rich sediments, some exceeding sand size, with their characteristic amorphous shape | Probably from charred plant-derived secretions (e.g. resin) the result of combustion activities, giving the | 104.2, 105.1, 107, 913.1 |

Table 2 (continued)

| Component | Description | Genetic interpretation | Thin sections |
|-----------------------|---|---|---------------|
| | with vesicles resulting from trapped air bubbles and dehydration cracks. In some cases, the charred mass is optically contiguous to wood charcoal. | common association with wood charcoal. The macrobotanical assemblage evidences a significant exploitation of pine (López-Dóriga 2016). | |
| Foraminifera | Few and poorly preserved isolated foraminifera were observed in shell-rich sediments. | Anthropogenic, non-intentional input associated with shellfish gathering in the estuarine marshes. | 104.1, 913.2 |
| Calcified filaments | Very common in shell-rich and especially in cemented sediments, filaments (100 µm or more in length and 5–10 µm wide) sometimes branching, reproducing the mycelial growth of fungal hyphae with (taphonomic) micritic nature and a characteristic inner hollow left after the fungi decomposition. | Charred and calcified fungi (<i>Cenococcum geophilum</i>) sclerotia have been identified in the macrobotanical assemblage and associated to ancient or dead wood exploitation (López-Dóriga 2016). These fungi also develop hyphae like those seen in thin section, too small to be recovered in flotation, but that can be related to the sclerotia species identified in the archaeobotanical study, also calcified. This correlates well with elements in the macrobotanical analysis. | All |
| Insect faecal pellets | Very frequent, both humified and calcified, oblong to spherical granules are ubiquitous. | Charred and calcified termite excrements have been identified in the macrobotanical assemblage at Poças de Sao Bento and associated with ancient wood exploitation (López-Dóriga 2016). Humic pellets (not charred or calcified), from other insects also occur, associated with recent bioturbation. | All |
| Phytoliths | Rare, elongated phytoliths were observed associated with the highly organic anthropogenic sediments, with possible signs of alteration. | Given their occurrence in highly organic anthropogenic sediments, they are possibly related to plant processing at the site by humans. | PSB108 |
| Fresh plant material | Roots, plant tissue and plant cells are ubiquitous elements, often in close association with humic faecal pellets. | Recent bioturbation. | All |

blocks from the profiles and using pre-plastered bandages to pack the exposed surface of the blocks and ensure their undisturbed extraction. After they were wrapped in plastic, the orientation was marked on each block.

The deposits in Area 1 are well representative of the overall site chronostratigraphic scheme explained above. Therefore, a vertical sampling strategy was undertaken (Courty and Fedoroff 2002) covering the full sequence in the North profile (samples PSB102 to PSB106) (Fig. 2c). The shell midden here consists of one homogeneous layer ~35 cm thick (stratigraphic unit 3/7). Additionally, two lateral samples were taken: PSB107 was collected in the contact between stratigraphic units 3/7 and 12 (Fig. 2c), distinguished in the field by the relative lower abundance of shells in unit 12; PSB108 was collected in the East profile in order to cover a zone of discontinuous calcareous concretions, which characterise the base of unit 12.

From Area 5, one thin section (PSB510) was analysed, from a heavily and homogeneously concreted area at the base of the shell midden layer, which here is quite thick (50–60 cm). As mentioned above, Area 9 deposits revealed the most complex superposition of clearly different shell-rich deposits. One large block sample covering the full sequence of these shell midden layers was collected in the West profile (Fig. 2) and resulted in four thin sections (PSB913.B1, B2, D1 and D2).

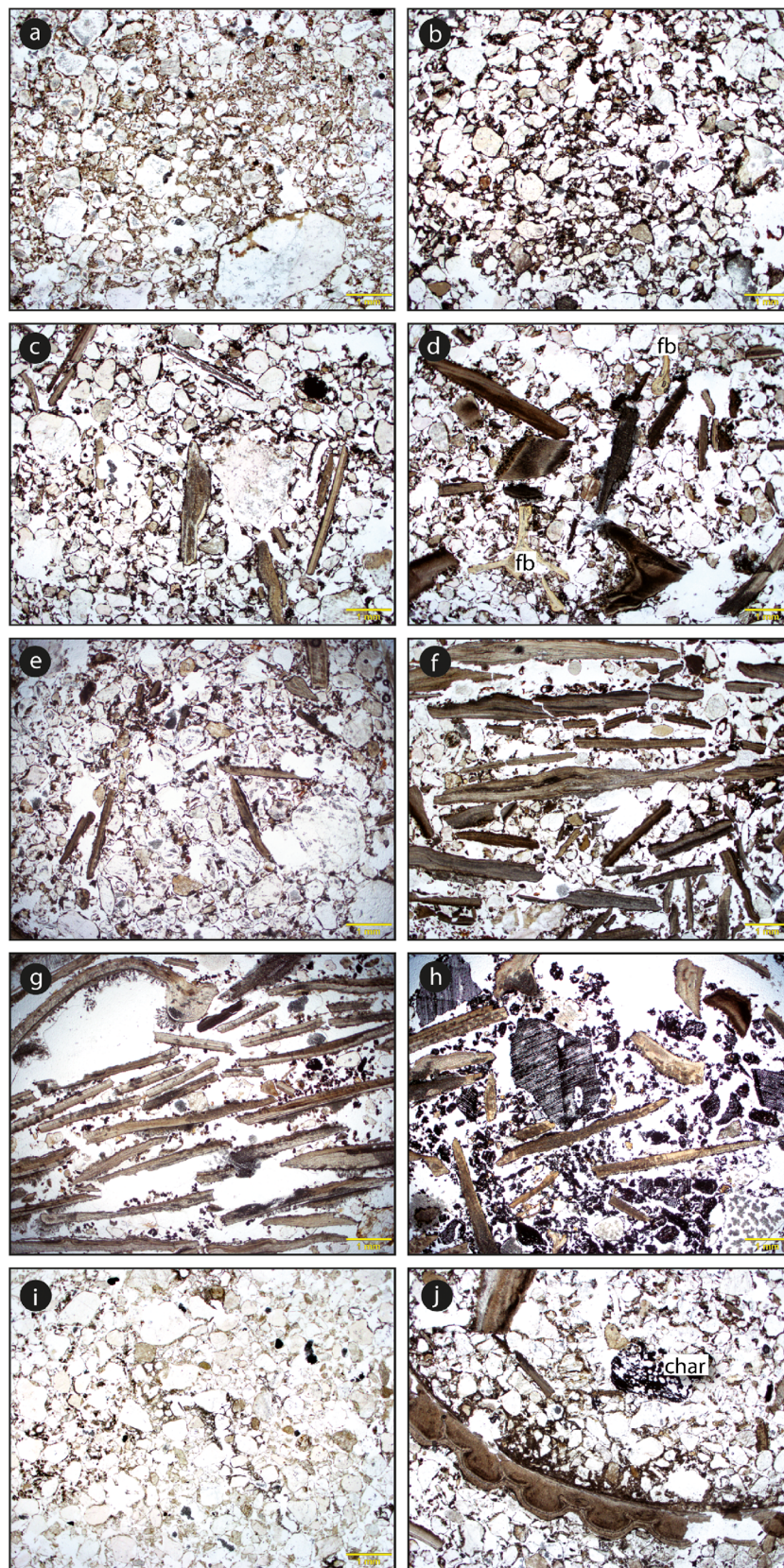
After drying, the samples were impregnated using a three-component synthetic resin mix (polyester resin, styrene and catalyst) at the facilities of the *Instituto Internacional de Investigaciones Prehistoricas de Cantabria* (IIIPC) and the *Departamento de Ingenierias Química y Biomolecular*, both at the University of Cantabria (UC) (Santander, Spain). Once totally consolidated, the blocks were cut into smaller slabs at the *Departamento de Ciencia y Ingeniería del*

Table 3 Description and interpretation of the microfacies types identified in Poças de São Bento thin sections and correspondence, when existent, with mF types at Cabeço da Amoreira (Aldeias and Bicho 2016)

| Microfacies type | Major characteristics | Corresponding mF at Cabeço da Amoreira | Genetic interpretation |
|---|---|--|---|
| 1, <i>Unsorted sand with clay</i> | Unsorted sand and organo-mineral microaggregates of variable sizes between the grains as well as partial coatings in the coarser grains. | – | Ap2-horizon. Recent ploughing activity |
| 2, <i>Sand and polymorphic fom</i> | High amounts of pellets and welded aggregates of polymorphic fom (30–40%), distributed between and coating coarser sand grains, forming a spongy microstructure. | – | A1-horizon. Middle Holocene Palaeosol |
| 2a, <i>Sand and polymorphic fom with few shells</i> | Same as type 2, but includes few shells (5–10%) strongly decalcified. | – | Surficial shell midden disturbed by pedogenic activity and post-Mesolithic admixture. |
| 3, <i>matrix-supported shells</i> - 3a, <i>Coarse heterogeneous</i> | Frequent shell fragments (30%), charcoal, bone, fishbone and char aggregates, all chaotically distributed. Heterogeneous micromass: moderate to strong secondary micritic infillings, organic silt particles and micro-charcoal between coarse components and coating the surface of coarser components. Abundant highly birefringent microcrystals, presumably of calcite and sericite, resulting from secondary precipitation and feldspar alteration, respectively. Occasional rounded pebbles of calcareous rocks exposed to high temperatures (calcination and cracks) and quartz. | 2, 4 | Anthropogenic reworking of activity debris (shellfish and other plant and animal processing refuse) by dumping or raking out. |
| 3 <i>matrix-supported shells</i> . Sub-type 3b, <i>Coarse inorganic</i> | Common shell fragments (20%). Mineral sand and silt grains are the dominant coarse components and very rare, fine sand sized charcoal and fewer bone. Scarce micromass (5–10%) mainly calcitic, with little organic silt, forming coatings and microaggregates between coarse components. Localised micritic cementations, coatings and hypocoatings increase in relation to mF type 3a. | – | Anthropogenic reworking of (mainly) shellfish refuse by dumping or rake out. |
| 4, <i>Horizontally oriented shells</i> | Common to frequent shells (30–40%) sub-horizontally oriented, organised in stringers of interconnected shells, overall still matrix-supported. Most shells exhibit burning alterations and in situ crushing. Some shells display calcitic pendants. Charcoal, fishbone and char are also present in this mF, along with occasional medium-sand size clay aggregates. The micromass and geogenic components are similar to mF type 3a. | 3 | Trampled occupation surface. |
| 5, <i>shell-supported sediments</i> . Sub type 5a, <i>Interconnected shells</i> | Practically all shells and some quartz grains exhibit calcitic pendants. High porosity (20–30%), characterised by packing voids. Occasional scattered charcoals (5–10%), several fish bones in a cluster and rarer isolated fragments. Clayey aggregates occur concentrated at the bottom of the deposits. Lenticular structures 2–4 mm thick of well-sorted, medium sized sand between the shells. Micromass is extremely rare and consists mainly of microcharcoal and microaggregates of organic and micritic composition. | 1a | Shell and debris tossing activity |
| 5, <i>shell-supported sediments</i> . Sub-type 5b, <i>Coarse wood charcoal</i> | Coarse wood charcoal and shells, in a ratio of 50/50 are the main components. Phosphatic nodules (5%) concentrated in clusters, probably result of decayed plant material. | – | Charcoal and shells tossing |
| 6, <i>Silty sands</i> | Single grains of silty sand clast-supported sand and domains of complete micritic infillings of the space between sand grains. | 5b | Pleistocene/Holocene sand cover |
| 6a, <i>Silty sands with few shells</i> | Differs from mF type 6 solely by the presence of few or very few shells (5–10%) and rarer fine-sand-sized charcoal, without any orientation pattern. | 5a | Dispersed shells in the sand by processes related to the active layer and reworked downwards by bioturbation |
| 7, <i>Calcitic cement</i> | Strong cementation by secondary calcite (micrite, needle fibre calcite and alveolar septal calcite) that infills the void space between the components almost completely (10% void space). | 1b | Carbonate cementation by secondary calcite (micrite and needle fibre calcite) |

Terreno y de los Materiales (DCITYM-UC) in order to create a regular surface, suitable for thin section production. The resulting slabs were mailed to Earthslides

(Cambridgeshire, UK), which produced 110 × 76 and 75 × 50 mm thin sections with the standard sample thickness of 30 µm, covered with a cover slip.



A total of 17 thin sections were produced and digitally scanned using a flatbed scanner (Arpin et al. 2002), in normal

and dark field modes (Goldberg and Aldeias 2016), for observations at normal scale and smaller magnifications. The

◀ **Fig. 3** Representative microphotographs of the microfacies types at Poças de São Bento. All in PPL. All scales are 1 mm. **a** mF type 1, sand with clay. **b** mF type 2, sand and polymorphic fine organic matter. **c** mF type 2a, sand and polymorphic fine organic matter with few shells. **d** mF type 3, matrix-supported shells, subtype 3a, coarse heterogeneous. **f** fishbone. **e** mF type 3, matrix-supported shells, subtype 3b, coarse inorganic. **f** mF type 4, horizontally oriented shells. **g** mF type 5, matrix-supported shells, subtype 5a, interconnected shells; note larger fragments of *Scrobicularia plana* shells. **h** mF type 5, matrix-supported shells, subtype 5b, charcoal and shells. **i** mF type 6, silty sands; note greyish zones corresponding to micritic infillings. **j** mF type 6a, silty sand with few shells; note char aggregate (*char*) and nearly complete *Cerastoderma edule* shell

optical examination was carried out using petrographic microscopes that allowed magnifications from $\times 20$ to $\times 400$ in plane- (PPL) and cross-polarised (XPL) light. The systematic micromorphological descriptions followed the terminology established by Stoops (2003) and Courty et al. (1989).

Results

Sedimentary components

The main sedimentary components observed in thin section are listed in Table 2, where detailed descriptions and brief genetic interpretations are also provided. Geogenic components are silt and sand mineral grains and few quartz, arkosic and calcareous pebbles. Silt and sand grains are mainly composed of medium to well-rounded quartz and feldspars, consistent with those observed from the Pleistocene/Holocene sand cover on which the shell midden rests. The pebbles are generally considered allochthonous, as they are not observed in the sand cover, and their presence is restricted to shell-rich anthropogenic sediments. These are, therefore, interpreted as anthropogenic inputs to the site.

Other anthropogenic-derived components comprise shells of peppery furrow (*Scrobicularia plana*), widely dominant, and the less frequent common cockle (*Cerastoderma edule*) (Fig. 3). Other components directly associated with human occupation include bone, particularly fishbone, sometimes with optical signs of burning (orange-reddish colour and loss of birefringence), wood charcoal and char aggregates (Fig. 3). Char aggregates, opaque masses with typical vesicles and cracks resulting from dehydration, are often attached to charcoals, with distinguishable carbonised cellular structure of the wood, which suggest that they correspond to charred plant-derived secretions, namely resin (Fig. 4a). The carpological analysis recovered charred and calcified insect excrements and also charred fungi anatomical parts (sclerotia) from anthropogenic sediments, which were considered to be ancient, possibly as result of exploitation of conifer wood, namely dead wood (López-Dóriga 2016). Our study corroborates the hypothesis, since we can observe, in

thin section, common micritic faecal pellets (Fig. 4b), equally charred sclerotia (Fig. 4c) and calcified fungal filaments (hyphae) (Fig. 4d, e), that can be linked to the afore mentioned macrobotanical elements. Some loose phytoliths were observed, in association with highly organic micromass (Fig. 4f, g), rich in dusty charcoal and secondary micrite, particularly common in thin section PSB108 (as seen in Fig. 4d). All these components are finely mixed with the organic micromass of anthropogenic sediments (Fig. 4). The rare presence of small clay aggregates and isolated foraminifera and ostracods in shell-rich sediments is regarded as unintentional by-products of shellfish gathering in estuarine marshes of the River Sado.

Microfacies

The most discriminating factor for microfacies (henceforth, mF) types identification at Poças de São Bento sediments were the relative abundance of shells and their organisation and orientation patterns. The different mF types broadly coincide with the stratigraphic units visible in the field. However, different geometric patterns, only observed in thin section, can be clearly distinguished within the shell midden layers and associated with specific human activities. A total of seven main mF types were identified in the thin sections from Poças de São Bento, with several subtypes. Table 3 summarises the major characteristics of each mF type, and representative microphotographs of each one can be found in Fig. 4. Some significant aspects for the interpretation of the formation processes of each mF type will be highlighted below. Detailed descriptions of each mF type are supplied in the Appendix.

Microfacies type 1 corresponds, mostly, to intensive agriculture practices carried out in recent decades, which involved remobilisation of sediments from elsewhere by means of heavy machinery. Therefore, we will not take mF type 1 into further consideration regarding the prehistoric occupations of the site.

Microfacies type 2 is discriminated by the micromass composed of polymorphic fine organic matter (henceforth, polymorphic fom), which is plant material decayed by the action of soil fauna in situ (Buurman and Jongmans 2005; Wilson and Righi 2010). Polymorphic fom generates pellets, more or less welded in aggregates (sensu Buurman et al. 2005) (Fig. 3b). We can distinguish a subtype, mF type 2a, that includes few shells showing marked dissolution features.

Microfacies type 3, *matrix-supported shells*, has common (25%) to frequent (30%) shells, but they are not the dominant component, not in contact with each other and lack any orientation pattern. Secondary calcium carbonate occurs here in the form of micritic infillings and coatings. Interestingly, foraminifera specimens were spotted only in the two subtypes of this

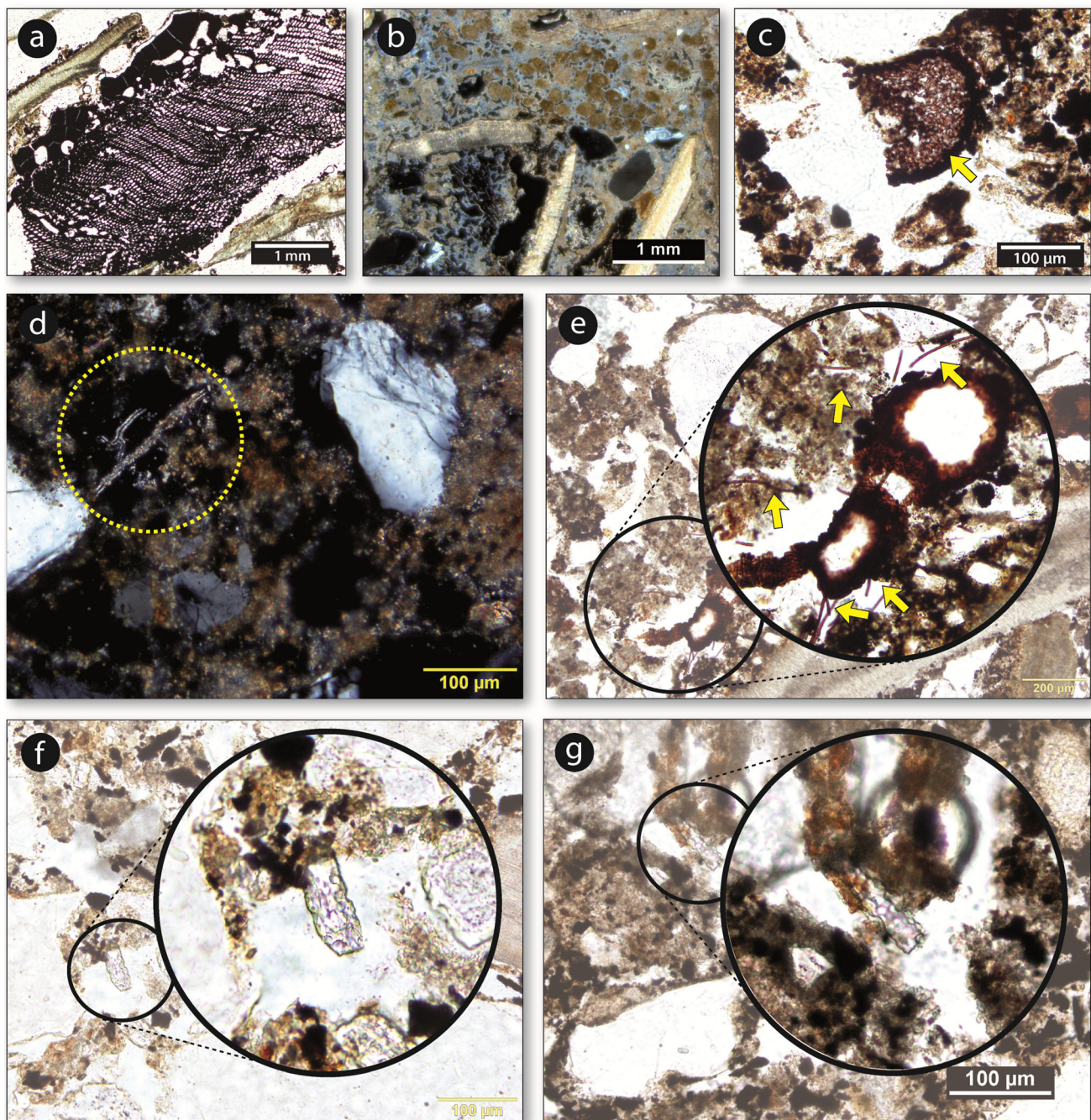


Fig. 4 Biogenic components of shell-rich anthropogenic sediments. **a** Wood charcoal and char aggregate from sample PSB913; note the carbonised cellular structure still preserved as charcoal; attached to it, note the amorphous mass with the vesicles (after air bubbles) and dehydration cracks typical of charred fats; in this case, most likely secretions such as resin, from the plant itself. PPL. Scale 1 mm. **b** Example of calcitic faecal pellets (concentrated at the top) in an also calcitic matrix,

a needle fibre cement, from sample PSB108. XPL. **c** Charred sclerotia (yellow arrow) from sample PSB108. XPL. Scale: 100 µm. **d** Calcified filaments (dashed circle), with the inner hollow after the fungal hyphae degradation from sample PSB108. XPL. **e** Example of not charred or calcified fungal material, with detail of fungal hyphae, from sample PSB108. XPL. Scale: 200 µm. **f, g** Examples of phytoliths, possibly with signs of alteration, from sample PSB108. PPL. Both scales are 100 µm

mF type. These subtypes are: (a) mF type 3a, with shells, charcoal, bone, fishbone and char aggregates, all chaotically distributed (Fig. 3d), and rounded pebbles of calcareous rocks

that were exposed to high temperatures (calcination and cracks); (b) mF type 3b is distinguished by slightly lower abundance of anthropogenic components such as shell

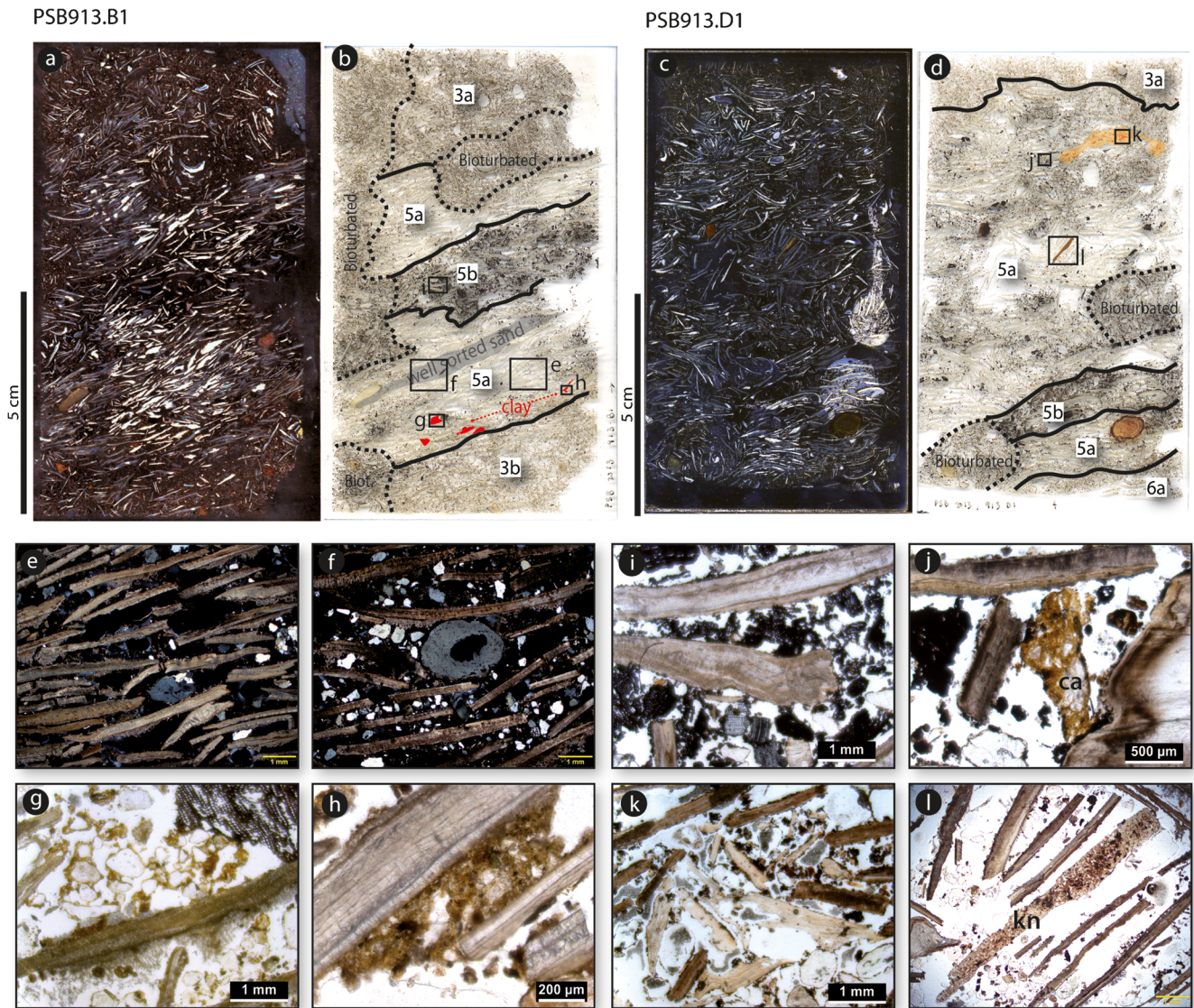


Fig. 5 Shell supported sediments: components and internal organisation. **a** Dark field scan of thin section 913.B1; note the superposition of different tossing events corresponding to mf types 5a and 5b and circular/crescent fabrics in bioturbated areas. **b** Same at normal light scan, with indication of microfacies and further annotations; *letters by the squares* indicate the corresponding microphotograph below. **c** Dark field scan of thin section 913.D1; note the fishbones held together highlighted in *orange* (detail in **k**); note the presence of several orientation patterns of the shells and circular/crescent fabrics in bioturbated areas. **d** Same at normal light scan, with indication of microfacies and further annotations;

the *letter in the squares* indicates the corresponding microphotograph below. **e** Detail of sub-horizontally oriented shells in mf 5a, note the lack of further components, XPL, scale: 1 mm. **f** Detail of the well-sorted medium sand lens, XPL, scale: 1 mm. **g, h** Two aspects of clay, coating and forming bridges between coarser components, PPL. **i** detail of mf type 5b, note the presence of exclusively wood charcoal and shells. **j** Examples of clay aggregate (ca), PPL. **k** Detail of the cluster of fish bones (lighter components), PPL. **l** Detail of the possible knapping residue (kn), PPL, scale: 1 mm

fragments (20%) charcoal and bone and increasing secondary micrite.

In mF type 4, the shells follow a sub-horizontal orientation pattern, organised in discrete stringers of interconnected shells, which are overall still matrix-supported. The shells show alterations induced by heating (brownish colour, loss of birefringence, as well as fissures parallel to the growth lines), according to archaeological and experimental evidence after Villagran (2014a) and

Aldeias et al. (2016). The shells also exhibit vertical fractures interpreted as in situ breakage i.e. the shells were crushed but remained in their position. These millimetre-thick stringers were not identified in the field, and the total thickness of the mF in thin sections is <2 cm.

Microfacies type 5 corresponds to deposits where shells are the dominant component, normally interconnected, without a preferential orientation pattern. However, the deposits corresponding to this mF follow a slightly oblique general

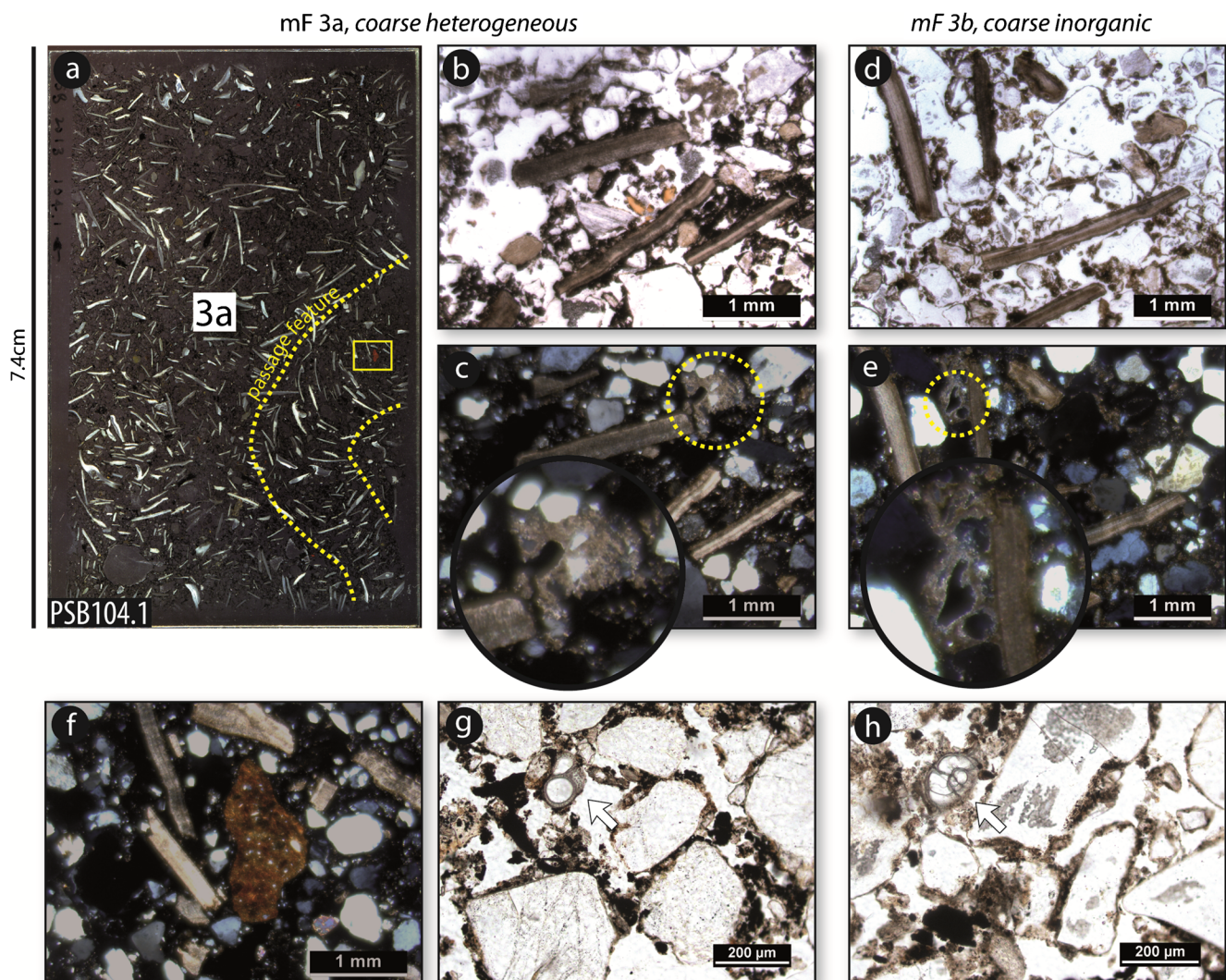


Fig. 6 Reworked anthropogenic sediments, microfacies 3a versus 3b. Microfacies 3a: **a** Dark field scan of thin section 104.1; note the lack of any organisation patterns of the shells and small size of fragments; the yellow dashed lines mark a bioturbated area, with shells organised in a crescent pattern; the square marks the reworked pottery fragment. **b** Groundmass of mF 3a, PPL; note presence of abundant organic matter (e.g. charcoal (dark material) and minute fragments of bone (yellow)). **c** Same as **b**, XPL; note localised micritic infilling, highly birefringent (dashed circle). **d** Groundmass of mF 3b, PPL; note the lack of organic

matter, compared to mF 3a (**b**). **e** Same as **d**, XPL; note the generally calcitic micromass (crystallitic b-fabric), with strong birefringence, and calcitic hypocoating (rhizolith, dashed circle). **f** Detail of pottery fragment biologically reworked into mF 3a sediments, as indicated by its microcontextual position inside the passage feature, XPL. **g** A foraminifer (white arrow) in mF 3a sediments, PPL, scale: 200 µm. **h** Another foraminifer (white arrow) in mF 3b sediments, PPL, scale: 200 µm

orientation in relation to the current soil surface (Figs. 2b and 5a) and have only been identified in Area 9. Two sub-types can be distinguished: (a) mF type 5a, with well-preserved features such as an interesting cluster of several fish bones observed in thin section PSB913.D1 (Fig. 5e, k), clayey aggregates concentrated at the bottom of the deposits (Fig. 5b, g, h), and 2–4 mm thick lenticular feature of well sorted, medium sized sand between the shells, as in thin section PSB913.B1 (Fig. 5b, f). A possible knapping residue is observed in thin section PSB913.4 (Fig. 5d, l); (b) mF type 5b, characterised by a striking dominance of wood charcoal up to gravel size.

Microfacies type 6 consists of single grains of clast-supported silty sand with domains of complete micritic infillings. A subtype, mF type 6a, differs from mF type 6 solely by the presence of few or very few shells and rarer fine sand sized charcoals.

Microfacies type 7 corresponded, in the field, to areas varying from 2 cm nodules to wide patches strongly cementated by secondary calcite that, as seen in thin section, infills the void space. The deposits corresponding to mF type 7 are in the base of shell midden layers, in the same situation as reported at Cabeço da Amoreira (Aldeias and Bicho 2016).

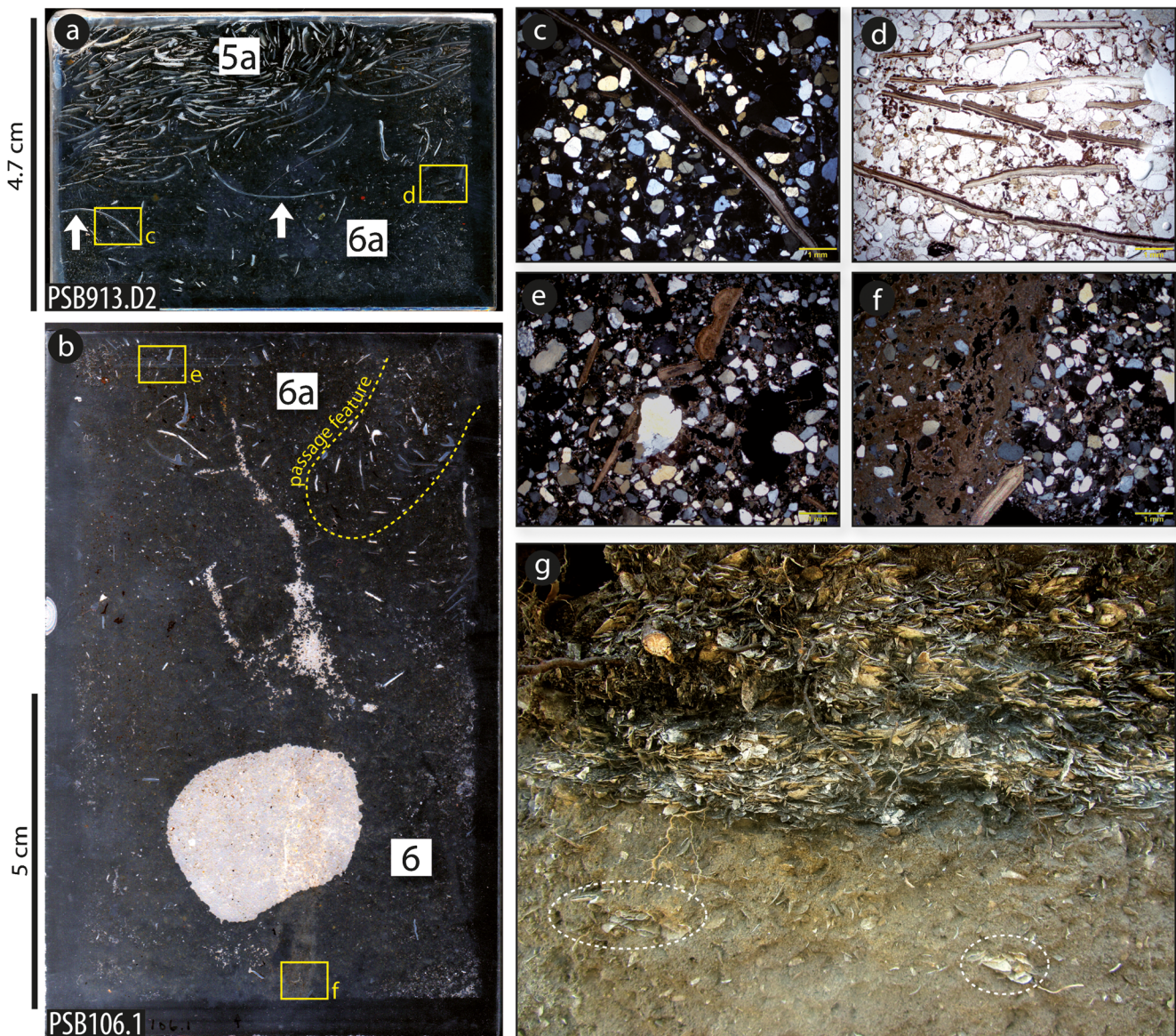


Fig. 7 The sand cover substrate. **a** Dark field scan of thin section PSB104.1, showing the contact between mF types 6a, *silty sand with few shells*, and 5a, *interconnected shells*; note the complete sections of *S. plana* (white arrow) surrounded by mF 6 s sediments, in horizontal position. The letters by the squares indicate the corresponding microphotograph to the right. **b** Dark field scan of thin section PSB106.1, with indicator of post-depositional movements of shells into the sand; note passage feature (dashed line) with shells in a crescent organisation pattern. The letters by the squares indicate the corresponding microphotograph to the right. **c** Microphotograph where it is clear that the complete valve of *S. plana* is surrounded by sand from the sand cover

(mF type 6a), XPL, scale: 1 mm. **d** Group of shells in mF 6a showing in situ cracking, PPL, scale: 1 mm. **e** Shell fragments in sub-vertical position, not clearly associated with bioturbation, XPL, scale: 1 mm. **f** Detail of micritic infilling of bioturbation feature, with a shell fragment in its limits, probably associated with biological reworking, XPL, scale: 1 mm. **g** Field photograph of Area 9 south profile, with the mF type 5, *shell supported sediments*, deposit overlying mF 6a sands; note the sub-horizontally oriented shells (dashed ellipses), laying a few centimetres below the shell midden deposit, surrounded by possibly reworked sands from the aeolian basal sands

Post-depositional features

The archaeological stratigraphy at Poças de São Bento is badly affected by post-depositional alterations. Recent ploughing, small mammals' burrows, biological (root and soil fauna) channels and localised concretions are some of the most striking disturbances visible in the field

(Fig. 2c). In the shell-rich sediments at Poças de São Bento, observing the micromorphological thin sections at 1:1 scale, it is possible to discern more accurately the extent to which these disturbances affect the stratigraphic record and track post-depositional movements of archaeological material. At the microscopic scale, post-depositional processes are readily identifiable, which

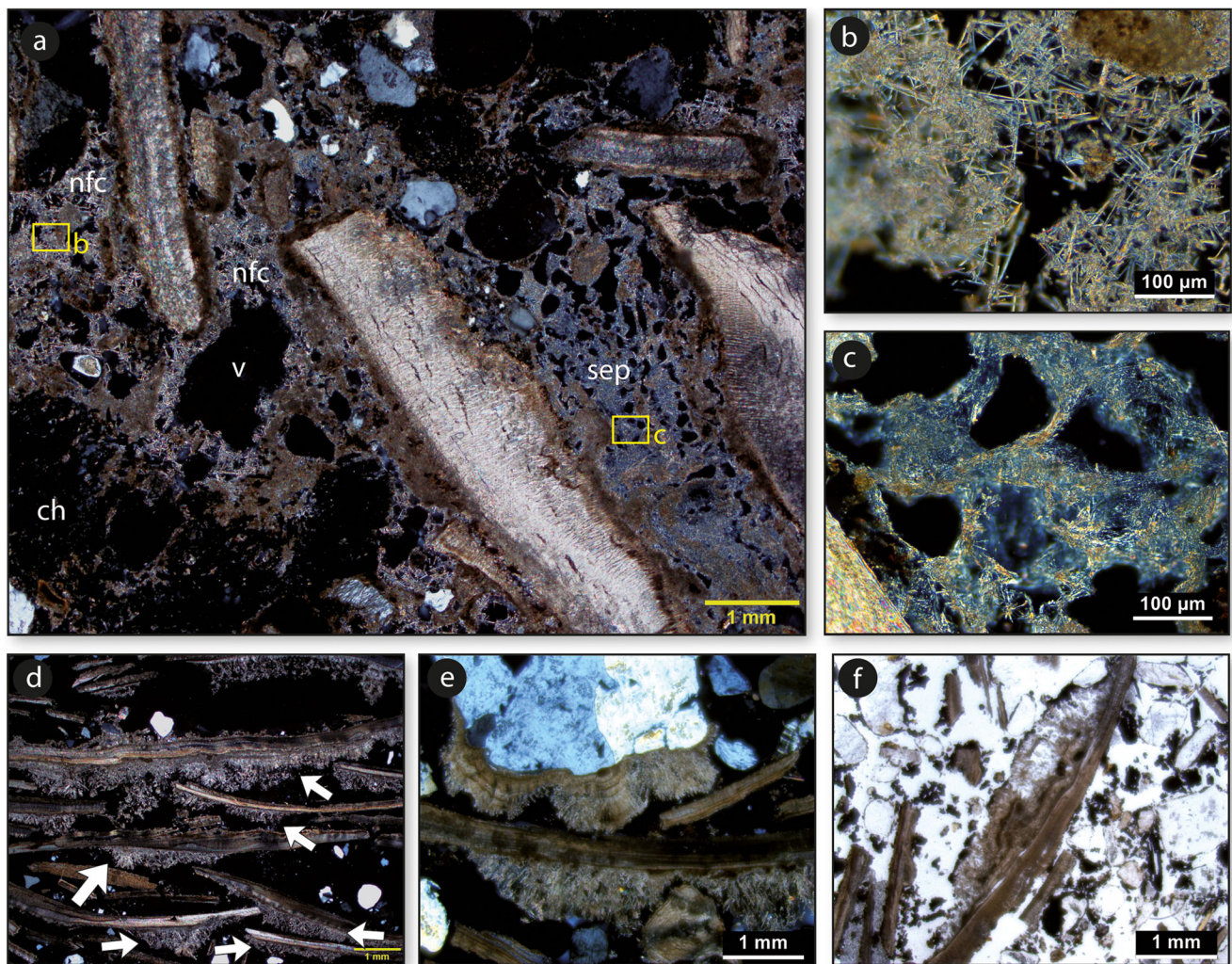


Fig. 8 mF type 7, *calcitic matrix*, and post-depositional crystallitic features. **a** Representative microphotograph of mF type 7 from thin section PSB510; note the several types of secondary calcite filling the void space (v) between shells and charcoal (ch). The letters by the squares indicate the corresponding microphotograph to the right. **b** Detail of needle fibre calcite, XPL. **c** Detail of alveolar septal fabric calcite, XPL. **d** Example of

calcitic pendants below interconnected shells of mF 5a in sample PSB913.B1, XPL, scale: 1 mm. **e** Calcitic pendants at higher magnification; note the elaborate example under a quartz grain, where the several layers representing different phases of crystal formation are visible, XPL. **f** Example of disturbed shells, as indicated by the calcitic pendant not in the original formation position, PPL

allows the preservation conditions of the anthropogenic materials to be addressed, a fundamental aspect of archaeological interpretation (Goldberg and Berna 2010). The post-depositional processes can be divided into two groups based on their implications for the integrity of the archaeological record at the site; these are crystallitic features and mechanical disturbance.

Crystallitic features

Crystallitic features result from calcium carbonate dissolution and reprecipitation. In the setting of the human settlement at Poças de São Bento, the presence of calcium is mostly due to the anthropogenic input of shells. Moreover, there are carbonated rocks in the broader

geological environment (Miocene sediments that have undergone pedogenic carbonation) (Pimentel and Azevêdo 1994), exposed in some points of the slopes of the Sado Valley. Some of these rocks were also anthropogenically introduced to Poças de São Bento alongside the incorporation of shells.

Dissolution is an important process affecting the shells at the site. In mF 2a, *sand and polymorphic fom with few shells*, this process is observed in the majority of shells, which overall present intense carbonate loss. Microfacies type 7, *calcitic cement*, can be interpreted as the result, also post-depositional, of this process: The carbonates secondarily precipitated in certain zones, originating cemented areas of shell-rich deposits, normally at the bottom of the deposits. Cementation of basal shell midden

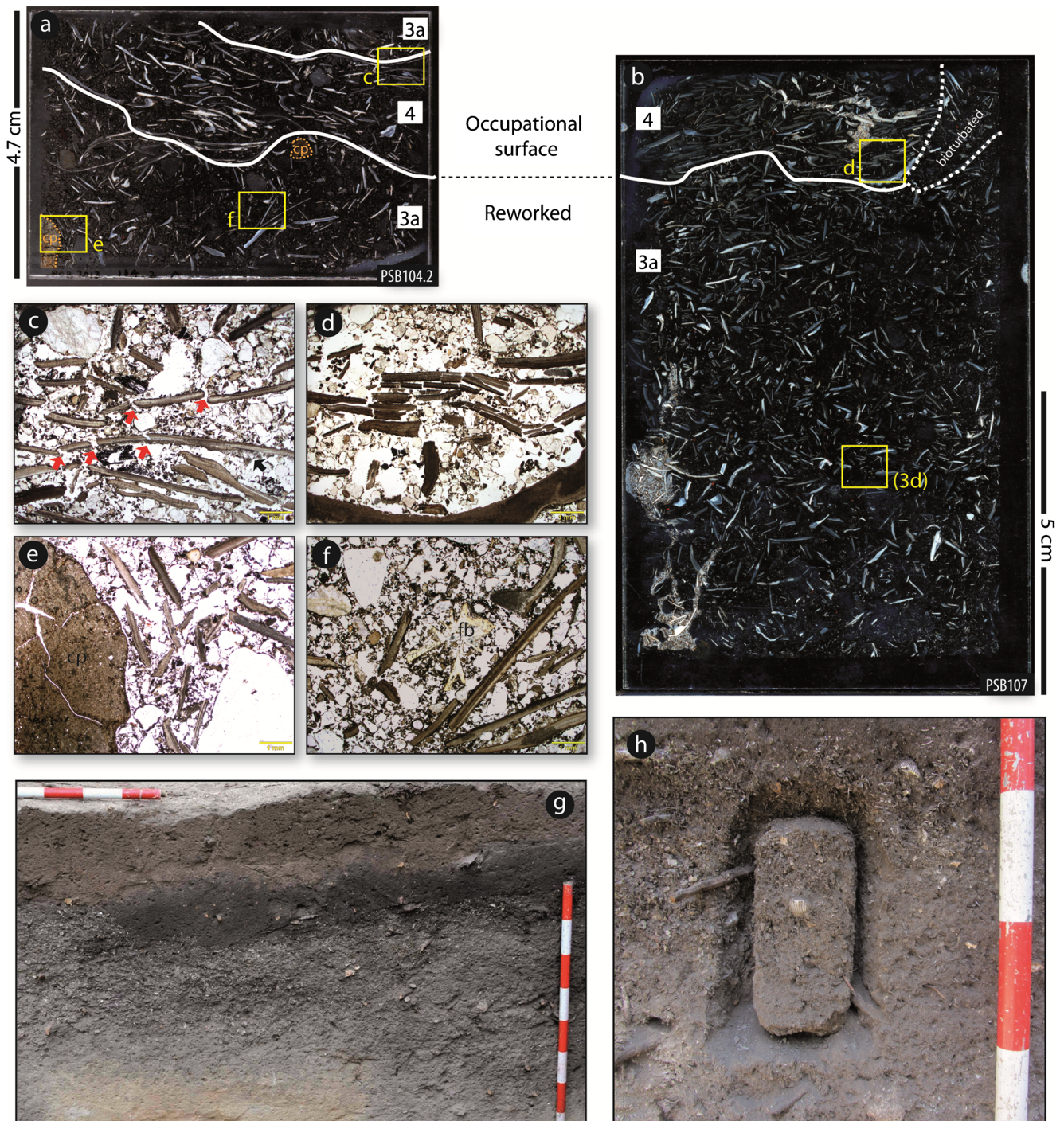


Fig. 9 Superposition of microfacies of anthropogenic sediments in Area 1; mf type 4, *horizontally oriented shells*, overlying mf type 3a, *coarse heterogeneous*. **a** Dark field scan of thin section PSB104.2, with mf contacts marked (*white lines*); note the calcareous pebbles (*cp*) in mf 3a. The *letters by the squares* indicate the corresponding microphotograph below. **b** Dark field scan of thin section PSB107, with mf contacts marked (*white lines*). The *letters by the squares* indicate the corresponding microphotograph below. **c, d** Detail of horizontally

oriented shells in mf 4; note in situ cracking (*red arrows*), PPL, both scales: 1 mm. **e** Detail of calcareous pebble; note the cracks, possibly due to exposure to heating, PPL, scale: 1 mm. **f** Detail of mf 3a, *coarse heterogeneous*; note the fish vertebra (*fb*), PPL, scale: 1 mm. **g** Aspect of the shell midden layer in Area 9 before the micromorphological sampling; note the homogeneity. **h** Closer view of the same profile during collection of the sample PSB107; mf type 4 is not perceptible (compare with the resulting thin section above)

deposits due to dissolution of the overlying shells by rain-water was noticed by Roche (1966) in Moita do

Sebastião, another shell mound in the Muge Valley, near Cabeço da Amoreira. Aldeias and Bicho (2016) also

described the phenomenon at the latter. The cement in mF type 7, *calcitic cement*, is formed by several types of precipitates, of which micrite is most abundant (30%), coating irregularly the components' surfaces and forming closed vughs. Micritic infillings and hypocoatings are also abundant in mF type 3, *matrix-supported shells*, particularly 3b, *coarse inorganic* (Fig. 6c, e) although without hardening these deposits, and constituting the very expressive, sometimes complete infillings of bioturbation features in the sandy mF types 6 and 6a (Fig. 7e).

Needle-fibre calcite is exclusively seen and very common in mF type 7, *calcitic cement*, formed by thin (0.5–2 µm wide) and very long (up to 100 µm), randomly oriented crystals forming a meshwork pattern, superimposing surfaces of voids in the micritic infilling (Fig. 8a, b). Another common type of cement at mF type 7 is the so-called alveolar septal fabric (Scholle and Ulmer-Scholle 2003) (Fig. 8c), forming narrow, curved septa consisting of bundles of even finer calcite needles (>0.5 µm wide and <2 µm long), barely perceptible under the petrographic microscope. Similar crystals have been interpreted as reproducing fungal mycelial shapes (Scholle and Ulmer-Scholle 2003) and attesting to a significant fungal presence in the deposit. Another element both in the cemented layers and, to a lesser extent, overlying shell-rich deposits are calcified filaments (Fig. 4d), threadlike structures corresponding to fungal hyphae encrusted with minute calcium carbonate crystals (Durand et al. 2010). Calcified roots or rhizoliths (Durand et al. 2010) occur in both cemented and non-cemented deposits (Fig. 6e). These post-depositional, calcitic features reach centimetre-thick dimensions in the cover sand deposits underlying the shell midden (Figs. 2c and 7f).

Another very common secondary calcite feature, unrelated to cemented deposits or biogenically induced calcite, is the aforementioned pendants. These structures are formed in meteoric vadose areas i.e. above the water table, where there is enough void space for water drops to hang from the underside of the grains (Scholle and Ulmer-Scholle 2003; Flügel 2004). At Poças de São Bento, the pendants, reproducing the drop shape, consist of alternating laminae, roughly parallel to the bottom surface of shells on which they formed. The laminae exhibit differences in colour, from limpid to brownish, depending on the amount of organic matter (Durand et al. 2010). They can become quite irregular in the outermost surfaces, because of varying crystal morphologies of each laminae, ranging from micritic to microsparitic and acicular calcite crystals, and overall are quite fibrous. The aggradation of repeated pendant layers (Fig. 8e, f) is common, forming fan-like structures, indicating several phases of partial water saturation of the deposits. Practically, all shells and some coarse sand/gravel grains in mF type 5a,

interconnected shells, exhibit pendants (Fig. 8d), and there are rare occurrences under some shells in mF type 4, *horizontally oriented shells* (Fig. 9c).

Mechanical disturbances

In thin section, it is possible to delimitate, with remarkable precision, the areas mechanically disturbed by soil fauna (mainly arthropods) that, while burrowing, rearranged the shells in crescent/circular patterns, forming passage features, easily recognised at normal scale analysis of thin sections (Figs. 5a, c, 6a, and 7b). Moreover, it is possible to affirm that shells in these areas have been disturbed because some of them exhibit shells with rotated pendants (Fig. 8f) i.e. pendants not in the original gravitational position, meaning that the shell was disturbed after the pendant formation. The degree of bioturbation at Poças de São Bento in the remobilization of archaeological material is an important issue. For instance, the secondary position of a pottery fragment, consistent with ages of mF type 2 deposits, downwards into Mesolithic mF type 3a sediments was observed in thin section PSB104.1, inside one of these passage features (Fig. 6a, f). These features, easily recognisable for their two-dimensional geometry in thin section, are not always perceptible in the field.

Discussion

The recognition of microfacies enables the reconstruction of different human activities and behaviours behind the accumulation of shells and other anthropogenic debris at Poças de São Bento. Moreover, it provides precise information on natural processes during the site's occupation and how it might have been modified by post-depositional processes. Broader geological information available has provided relevant clues for the interpretation of human behaviour in the construction of shell middens at Poças de São Bento. In the next sections, we will address those questions, based on the geoarchaeological record studied with the mentioned methodologies.

The sand cover substrate

The interface between sterile dune sand and the first occupational deposits is difficult to pinpoint. There is no sharp contact from utterly “clean” sands, in terms of anthropogenic material, to shell-rich sediments. MF type 6, *silty sands*, corresponds to the lowermost and cleanest sands. The minute and extremely rare shell fragments in the mF appear to be post-depositionally displaced by root activity. This is supported by the microcontext of these

fragments, characterised by micritic impregnations around roots (Fig. 7e, f).

In the overlying mF 6a, *silty sand with few shells*, the number of shells progressively increases towards the contact with shell midden layers and reaches a relative abundance in thin section of 5–10%, in the immediate 10–20 cm below the shell midden, in both Areas 1 and 9. These sediments exhibit a grey colour in the field, and the contact with the lowermost yellow sands is gradual and marked by macroscopically visible bioturbation features, such as root and insect channels. We attribute the grey colour to the precipitation of secondary carbonates, which are visible in thin section.

In sample PSB913 (Area 9), within 2–4 cm below the lower contact with the shell midden, mF 6a presents some remarkable aspects regarding shell positions. One is that the shell fragments are randomly oriented, many in vertical position, but not associated with bioturbation features that explain their presence as post-depositional. Thus, their presence here must have another origin (Fig. 7a, c, d, g). Aldeias and Bicho (2016) previously noted that shells in vertical position were most likely deposited together with the surrounding sediment (otherwise, if not supported by the sandy matrix, the shells would tend to fall to a more natural horizontal position) which suggests that these are reworked sands that already contained shells. Another interesting aspect in thin section is the case of two nearly complete sections of *Scrobicularia plana* valves in sub-horizontal position; these were also perceptible in the field, where sometimes, several horizontal shells, crushed in situ and surrounded by sand, were found. However, as noted above, these intact valves point to little transport. Given that the matrix is undoubtedly the same as the Pleistocene/Holocene cover sand, we interpret the first (upper) few centimetres of mF type 6a deposits, at least in Area 9, as an active layer i.e. a rather unstable sand surface, susceptible to particle movements. The shells in these surficial sands may have arrived by dispersion. So far, there is no field evidence of such deposits, so this remains open as a hypothesis for future work.

Dispersion of shells can result from many factors. Wind is an important natural agent in sandy settings, promoting surficial creep of silty-sand sized materials and rolling and saltation of coarser particles (French 2003; Courty et al. 1989), where shell fragments would be equally affected. Dispersion by human trampling is also a possibility that was taken into consideration for a similar mF type described at Cabeço da Amoreira (Aldeias and Bicho 2016). The fact that some horizontally oriented shells in these sands display in situ crushing (Fig. 7d), resembling those in mF type 4, could mean that some trampling was responsible for shell dispersion and incorporation in the surficial sand. Nevertheless, apart from the

described microcontextual evidence of some shells in the surface having arrived with the sand by particle movements, in lower depths (from the first 2–4 cm downwards), bioturbation is considered the main agent for post-depositional migration of shells of mF 6a deposits. Bioturbation has long been considered a major factor in vertical displacements of archaeological material in sandy settings (Goudie 2017). The OSL date of 12 ± 1 ka seems to support this. The dated sample comes from the middle part of the ~20 cm thick stratigraphic unit 912 (Area 9, see Fig. 1), containing shells, corresponding to mF type 6a. In sum, the date refers to a moment of sand accumulation and stabilisation at the end of the Pleistocene (see Table 1), thus incompatible with any human occupation so far identified at Poças de São Bento. With micromorphology, however, we can track more precisely the extent of movements by at least roots and insects (those of larger animals like rodents, mustelids or rabbits are clearly visible macroscopically). The recognition of such movements and microcontextual observations like those mentioned above (fragmented versus complete valves, organisation pattern and association or not with rhizoliths) indicate that some of the shells, in the first few cm, were deposited with the matrix.

Anthropogenic formation processes: human activities at Poças de São Bento

The microfacies approach to the shell midden layers at Poças de São Bento allowed the discrimination of specific, intact characteristics of its internal microstratigraphy and the association of each one to anthropogenic actions, divided into three main types of activity. As already stated, very interesting and remarkable similarities were found with some of the mF types, corresponding to shell-rich deposits, described at the site of Cabeço da Amoreira (Aldeias and Bicho 2016). This site is a larger shell mound, forming an artificial hill perceptible in the landscape. It is one of a group of Mesolithic shell mounds known in the Muge Valley, part of the early Holocene palaeo-estuary of the Tagus River (for details, see Bicho et al. 2013, 2011), located approximately 100 km north of the Sado shell middens area (Fig. 2). Given the similarities in the mF between the two sites, an outcome with valuable broader implications, here, we follow the nomenclature proposed by Aldeias and Bicho (2016) for anthropogenic activities (see also Villagran et al. 2011). For a correlation of the mF types and their respective brief interpretation at Poças de São Bento, linked to mF types at Cabeço da Amoreira, see Table 3.

Single tossing events

Microfacies type 5, *shell supported sediments*, is thought to be the result of preserved single events of direct tossing of

debris, mainly shells. These are often interconnected and parallel to each other, albeit not according to a single systematic orientation, and exhibit a low degree of fracturing. These deposits were identified in Area 9 and Area 5, although the latter was secondarily cemented. In thin section, features like fishbones maintained together (Fig. 5d, k) and 2–4 mm thick lens of well sorted medium-sand sized mineral grains (Fig. 5b, f) indicate little disturbance after deposition, thus possibly rapid burial. Clay coatings (pale yellow, stipple-speckled b-fabric) and interstitial clayey aggregates (Fig. 5g, h, j) contrast with the poorly sorted silt to coarse sand in the substrate, where clay is inexistent. For this reason, the well-sorted sand grains and the clay aggregates are interpreted as coming from a different source, possibly the estuarine marshes where shellfish was gathered using sediment-bearing techniques; it would suggest transport of the shellfish from the gathering place directly to the site of Poças de São Bento. This aspect reinforces the importance of the on-going sedimentological research on the Sado Valley infill, which is partially aimed at clarifying issues such as this. It is interesting to note that mF 5a is the only one where most of the shells exhibit well-developed calcitic

pendants, sometimes very elaborate, indicating several events of partial water saturation (Fig. 8d, e, f).

Like in the mF type at Cabeço da Amoreira also interpreted as single tossing events (see Table 3), the shells in Poças de São Bento's mF type 5a show some in situ cracks. Although, at Poças de São Bento, these features are not as overwhelming as at Cabeço da Amoreira, where the shells follow only one consistent, sub-horizontal orientation pattern, and in situ cracks are abundant (see Figs. 4 and 5a in Aldeias and Bicho 2016), we argue that they similarly have suffered some trampling, but perhaps not repeatedly. A microfacies type at the recent shell midden of Túnel VII, Tierra del Fuego (Argentina), also with interconnected shells in sub-horizontal, oblique and sub-vertical orientation patterns, was interpreted as “tossing of discarded items on the hut outer perimeter where the Yamana used to deposit the waste of daily indoor activities” (Villagran et al. 2011). The characteristics of mF type 5a at Poças de São Bento resemble more closely this organisation pattern. Aside from the differences in thickness between Túnel VII (up to 50 cm) and Poças de São Bento (10 cm), and taking into account the evidence of the mentioned well preserved microcontextual arrangements, we

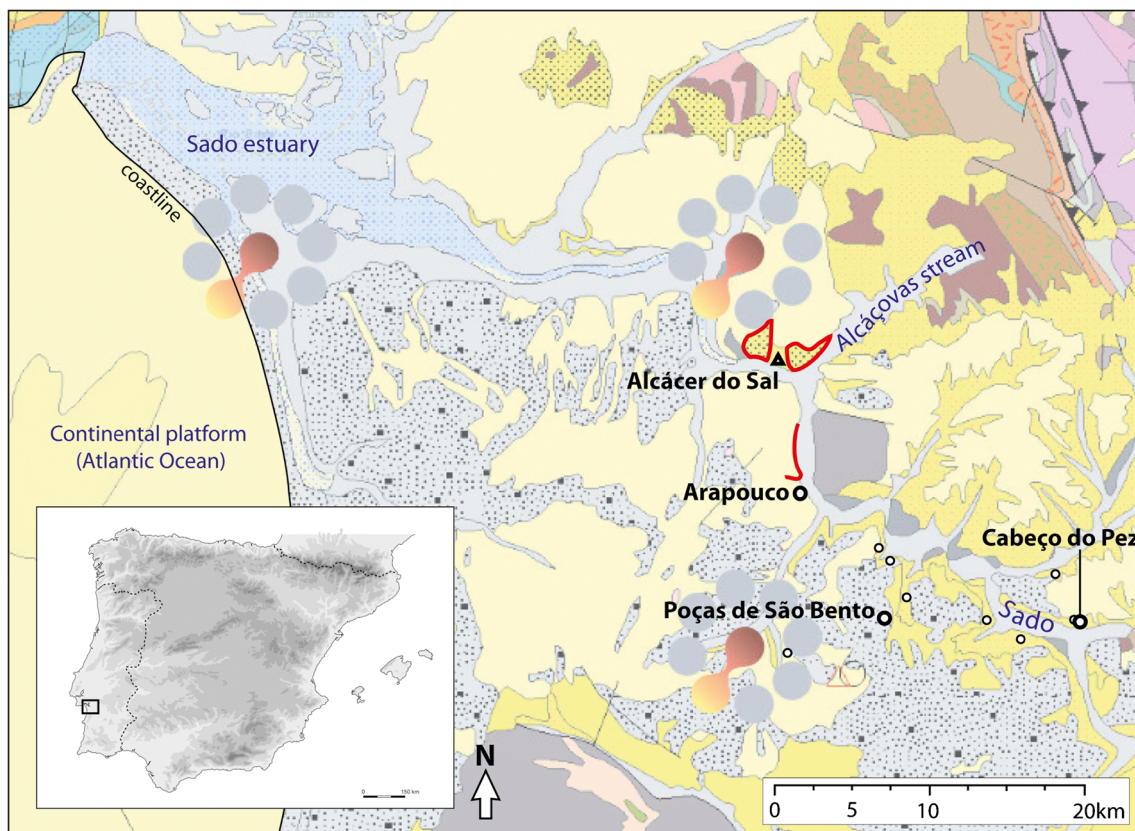


Fig. 10 Geologic map of the Sado shell middens area, with location of the town of Alcácer do Sal, Poças de São Bento, Arapouco, Cabeço do Pez and the other known shell midden sites (white dots). Note the outcrops of Miocene calcareous rocks mentioned in the geological

cartography, delimited in red. Note the present day estuary. Geologic map source: Laboratório Nacional de Engenharia e Geologia, Carta geológica de Portugal 1:500,000, version available online

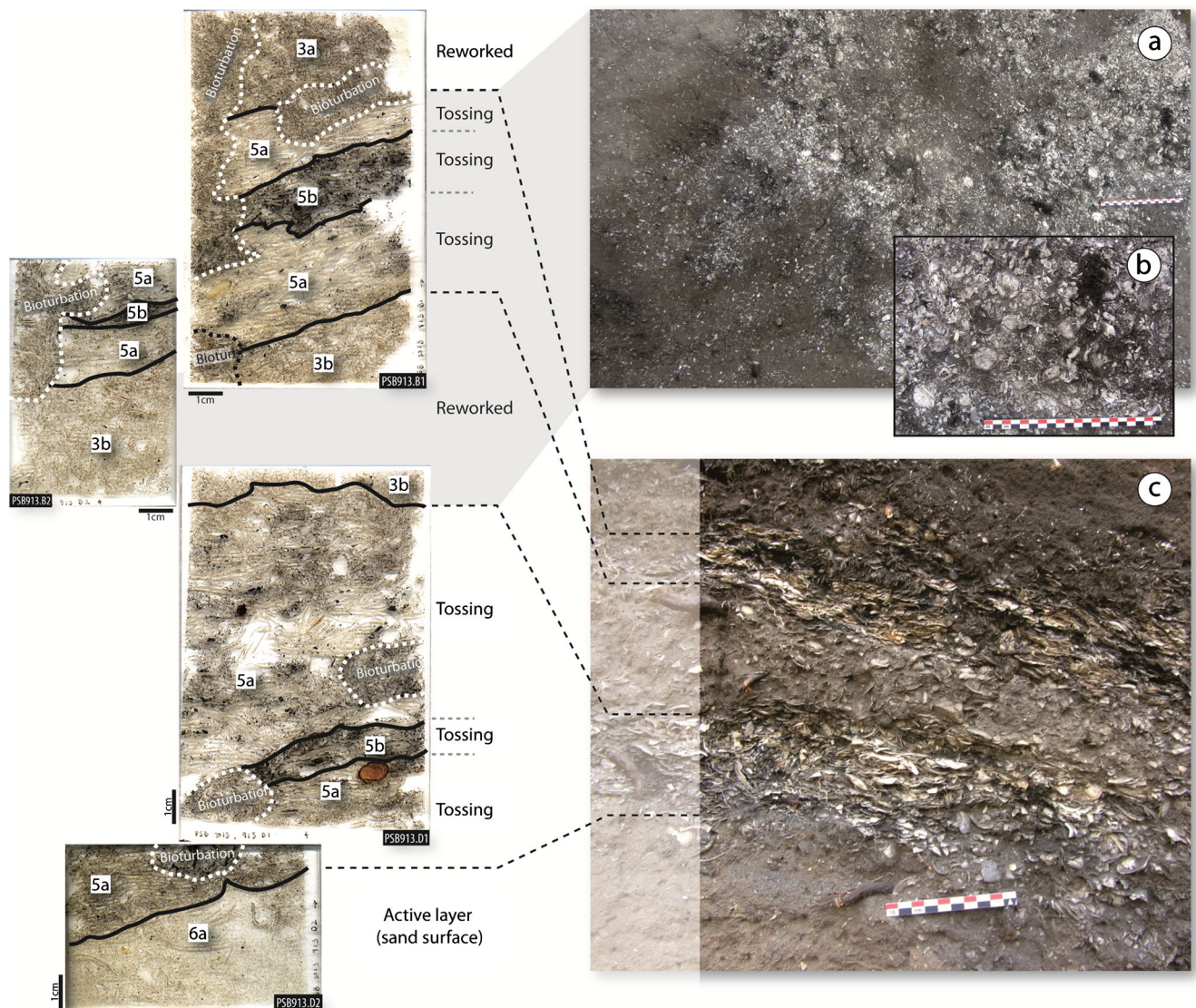


Fig. 11 Hypothetical reconstruction of the events involved in the accumulation of the shell midden layers in Area 9, based on the four thin sections from sample PSB913 (to the left; see also Fig. 2b), with indication of mF type boundaries and assigned activities. **a** Plan view of the excavation of mF5 deposit (right side of the photo, mostly complete shells) and contact with the underlying mF 3b deposit (left side of the

photo, shells are fragmented and matrix-supported); note the diffuse perimeter of mF 5 deposit, scale: 20 cm. **b** Close-up on mF 5 deposit; note the quite complete shells. **c** Close-up of the corresponding zone of the profile before sampling; note that only major events are clearly discernible in the field photo; scale at 20 cm

may think of a similar deposit of discarded activity debris, in an area of the site not continuously occupied and probably covered shortly after deposition.

The interpretation of mF subtype 5b, *coarse charcoal and shells*, is revealed by the high porosity and the shells' orientation pattern, which suggests also a single tossing event, but of more selected material: Only coarse charcoals and shells, in equal proportion, seem to have been tossed. We may tentatively think of different activities as the origin of the selection of components. Perhaps, mF 5a components were generated from the processing and consumption of shells and fish, whereas mF 5b could be the

result of disposal of fire residues from a cooking structure e.g. roasting with fire on top of the shellfish in a *cuvette* and later removal of the charcoal, as proposed in one of the experiments by Aldeias et al. (2016). Furthermore, there are no micromorphological indicators that this is an in situ combustion event, such as heated substrate or ashes which should be preserved, given the basic pH provided by the shells. Microfacies 5b was identified clearly in thin section 913B1, with a thickness of 1.5 cm, between two deposits corresponding to mF 5a (Figs. 2b and 5b), and there are other possible mF 5b domains in lower PSB913D1 thin section (Fig. 5d).

Based on the above, we argue that the *shell supported sediments* of mF type 5 correspond to the superposition of single tossing events, in primary position. When excavated, these deposits exhibit a maximum thickness of ~10 cm and have irregular upper contacts (Fig. 2b), as well as irregular boundaries in plan view. Despite intense disturbance by roots, which complicates the visualisation of the original shape, this spatial geometry makes us think of extended deposits, although still spatially well delimited.

Reworked anthropogenic deposits

The microfacies approach allowed the recognition of anthropogenic shell-rich deposits that were not in primary position but had been reworked. These correspond to mF type 3, *matrix-supported shells*, which had two subtypes. Subtype 3a, *coarse heterogeneous*, contains randomly orientated and distributed shells, including several in vertical position, which, together with a high degree of fragmentation, suggests that they were deposited with the matrix that supports them. The randomly distributed charcoal and fishbones, indiscriminately burnt and unburnt (5b and 8f), also support this interpretation, in contrast with the concentrated distribution patterns of these types of remains in mF type 5a. The high abundance of organic components in both coarse and fine fractions is related to animal and plant processing for consumption, here in secondary position.

In mF type 3a, there are also geogenic components such as small calcareous pebbles, and these are equally interpreted as anthropogenic inputs, based on the fact that the lithologies do not occur in the local Pleistocene/Holocene basal sand and that they are absent in other mF types. However, they occur in the broader geological region (Fig. 10) where calcareous rocks occur in Miocene outcrops in specific localities towards the bottom of the Sado Valley, that is, downstream from the site. It does not seem likely that they could have been brought to the site by a natural agent given the relief and distance. The clasts are too small (0.5 up to ~5 cm) to be suitable for any recognisable activity, leading to the exclusion of an intentional transport to the site. Indeed, there is no evidence of using them as raw material for lithic tools production, as there are for other allochthonous rocks (Pimentel et al. 2015). Instead, it is more likely that they relate to sediment-bearing shellfish gathering techniques in the Sado estuarine marshes, where they would be naturally deposited by slope and fluvial processes. Miocene calcareous rocks occur at the bottom of the valley, on the banks of Arapouco (the most downstream shell midden) and at the confluence of the Alcáçovas brook with the Sado (Fig. 10), outside the shell middens area. Therefore, the areas of the valley adjacent to the mentioned outcrops,

where calcareous rocks are more exposed and susceptible to erosion and reworking into the fluvial bed, could be the source of the calcareous pebbles. They show some evidence of exposure to fire e.g. cracks and calcination (Fig. 9a, e), eventually related to the combustion activities in which charcoal and burnt bones and shells of mF type 3a would have originated. Foraminifera (Fig. 6g, h) are another significant component, identified exclusively in mF types 3a and 3b, associated with an estuarine marsh environment and equally interpreted as a by-product of shellfish gathering. For all these reasons, we interpret the presence of calcareous pebbles as unintentional inputs brought with the shellfish by the Mesolithic occupants of Poças de São Bento. Furthermore, this hypothesis can indicate the preferential location of shellfish gathering, which might not have been carried out near the site, but ~8–12 km downstream in the river.

Overall, mF type 3a is interpreted as intentional anthropogenic displacement of previously deposited sediments, mixing remains from different activities, possibly by dumping or raking-out. The resulting deposits, according to experimental studies (Miller et al. 2010), also exhibit a high porosity and chaotic organisation of poorly sorted, burnt and unburnt components. Given the considerable extension of mF type 3a deposits in Poças de São Bento, it seems that the occupants of the site proceeded to spread these sediments around, in more or less juxtaposed accumulations. Such accumulations exhibit gradual horizontal boundaries in the field. A possible cause of reworked anthropogenic deposits, proposed by Aldeias and Bicho (2016) at Cabeço da Amoreira, is that the occupants were attempting to level the area in order to create a more stable and flat surface. Accordingly, we suggest a similar type of activity at Poças de São Bento.

Concerning mF type 3b, *coarse inorganic*, its main difference is a scarcity of organic components compared to mF 3a, and a predominance of silty sand matrix, abundant micritic impregnations and randomly distributed, fragmented shells. The micromass of mF type 3b is also less organic when compared to mF type 3a. The lesser abundance of anthropogenic components other than shells seems to indicate that this mF type might have resulted from reworking sediments that originally also did not contain such components. The origin of these sediments is for the moment unclear, but a possible explanation could be an older reworking history that could have progressively eliminated the organic components. Microfacies 3b was identified only in Area 9. The thickness of this deposit (~10 cm.) and lack of any internal sedimentary structures (e.g. graded or well sorted bedding) lead us to exclude a natural process as responsible for this deposit, since it would imply a localised high-energy event, which is difficult to envision. This deposit over- and underlies two

different deposits of mF type 5a (Fig. 2b and 11), thus indicating that the shell midden sequence at Area 9 was formed by alternatingly events of single tossing and mass loads of reworked sediments.

Occupational surfaces

Microfacies type 4, *horizontally oriented shells*, is individualised by the occurrence of discrete stringers of interconnected shells, in sub-horizontal position, with high degree of in situ crushing (Fig. 9c, d). These attributes are interpreted as the result of intense trampling, pointing to possible remains of occupational surfaces i.e. the exposed surface of an area of the site that people frequented more. It is not possible to individualise these sediments into field excavation units, but the unifying attribute of mF type 4 (stringers of interconnected shells crushed in situ) displays remarkable consistence in two thin sections. The corresponding samples, PSB104 and PSB107, were collected at similar elevations in the North profile of Area 1 and are separated from each other by c. 1 m, suggesting that they are the same layer (Fig. 9a, b; see also Fig. 2c for spatial correlation between the two samples). The sediments of mF type 4, *horizontally oriented shells*, overlie anthropogenically reworked mF type 3a sediments in both thin sections. This is one of the most interesting outcomes of the microstratigraphic approach at Poças de São Bento, since it reveals internal stratigraphic consistency within the quite extensive, apparently homogenous, (and only) shell midden layer in Area 1. Another valuable outcome is that this association of possible occupational surfaces overlying anthropogenically dumped sediments is also present at Cabeço da Amoreira shell midden, an association used by the authors to reinforce the inference that mF 3a sediments were dumped to flatten the surface (Aldeias and Bicho 2016). More samples would have to be analysed from further mF type 3a deposits in other areas of the site to make site-scale extrapolations. In Area 1, mF type 4 is also overlaid by mF 3a, and thus it seems that a new load of reworked anthropogenic materials was dumped over an occupational surface.

In Area 9, the mF type 3b, *coarse inorganic*, also interpreted as an anthropogenically reworked deposit, is not overlaid by mF type 4, *horizontally oriented shells*. Further research on the differences between mF types 3a and 3b in other parts of the site would possibly clarify a probable difference also in the intentions behind the general dumping actions argued for on mF type 3, *matrix-supported shells* sediments.

Dune stabilisation: the middle Holocene palaeosol

The Pleistocene/Holocene sand cover, and the shell midden resting over it, reached a period of stabilisation that allowed the development of a vegetated A horizon, which

has been classified as palaeosol A1 (phase C of Arias et al. (2015); see Table 1). These sediments correspond, in thin section, to mF 2, *unsorted sand and polymorphic fine organic matter*. The sand grains in mF 2 are more poorly sorted than in underlying deposits, with higher abundance of coarse sand grains, especially when compared to the Pleistocene/Holocene sand cover. This suggests the onset of a different sediment source, which is somewhat difficult to identify. Elsewhere, Duarte et al. (2015) suggested that this phase represents a shift in the environmental conditions that allowed the development of the palaeosol A1, which was inferred to represent more water availability from rainfall. The enrichment in polymorphic fine organic matter and the spongy microstructure are the key elements indicating that this deposit corresponded to a vegetated surficial soil. Polymorphic fom has been commonly found in spodic horizons (Buurman and Jongmas 20,015) (podzols have been reported in the area by Arnaud (2000)) but also in well-aerated, sandy soils. Curiously, it occurs in Brazilian “shellmounds with a sandy core” described by Villagran (2014b), although, here, polymorphic fom is related to anthropogenic inputs of organic carbon. In Poças de São Bento, there is no clear indicator that this amount of organic matter could be anthropogenically introduced, given the general lack of anthropogenic structures in this layer. The action of microbial and mesofaunal transformation of plant material into degraded and more or less welded organic aggregates of polymorphic fom takes place in the A-horizon of vegetated soils, which can occur with spongy microstructures (Wilson and Righi 2010), as in the case of mF 2.

The striking black colour of these sediments in the field (Fig. 2b, c) is due to organic matter, and its maximum thickness (c. 40 cm) suggests that this soil was exposed for a considerably long time (e.g. centuries), which led to the development of a thick vegetation cover. Furthermore, the fifth millennium cal BC radiocarbon dates obtained for samples of total organic matter from palaeosol A1 at the top of this layer in Area 6 (see Table 1) are consistent with the archaeological content of this layer, including sparse pottery sherds. However, the nature of the Neolithic presence at Poças de São Bento (as in other shell midden sites of the Sado Valley) remains an open question.

The palaeosol formation processes triggered some post-depositional alterations observed in the studied sediments. Soils are the dynamic product of chemical and physical weathering, and biological processes. Of particular interest at Poças de São Bento is the loss of material during periods of hydrologically effective precipitation, which leads to calcite dissolution and reprecipitation lower in the soil profile (Fairchild and Baker 2012). The soil

microbial community, inferred from the studied sediments, is a source of soil CO₂, along with root respiration (Witkamp and Frank 1969); this CO₂ generates the soil water acidity that enhances hydrolysis reactions, and the dissolution of carbonate clasts (shells). In our case, chemical weathering of Mesolithic sediments is evident by the hydrolysis of feldspars and their alteration to sericite (the main alteration mineral for feldspars and petrographically recognisable by small equidimensional crystal masses of grey to black interference colour replacing the feldspar crystal) and the partial dissolution of shell fragments in mF type 2a, the most surficial shell-rich sediments. The reprecipitation of these carbonates, lower in the soil profile, generates the pendants and the cemented areas in mF types 3, 6 and 7 (Figs. 6c, e and 8).

Spatial organisation

The human activities inferred from the micromorphological observation of anthropogenic sediments at Poças de São Bento revealed a clear intra-site differential use of space.

In Area 1, the shell midden layers revealed an occupational surface with signs of intense trampling, overlying a dumping of reworked activity debris, suggesting that this area was intensively occupied. Furthermore, in Area 1, the shell midden layer filled a pit excavated in the sand cover (Fig. 2b), a type of feature normally associated with residential purposes. In the future, micromorphological analysis of this pit infill (shell-rich sediments macroscopically homogeneous and similar to the shell midden layer itself) can potentially provide more detailed data on this aspect. The shell midden layer in Area 1 also contained the dog burial, evidence of more symbolic behaviour, in an area of the site that was occupied intensively.

The overlapping of different types of anthropogenic deposits in Area 9 suggests that this location corresponded to a preferential area of refuse of food items (shells and fish). Several superimposed single tossing events, intercalated with at least one sediment dumping event, can be clearly distinguished in thin section (Fig. 2b and 11), suggesting that this specific location was used mainly for that effect. Little trampling and rapid burial indicators seem to suggest that Area 9 was immediately adjacent to a location where food consumption activities and subsequent tossing of the resulting debris repeatedly took place. This inference is interesting at the level of site-scale interpretations, given the proximity of Area 9 to the funerary area at Poças de São Bento.

Living in the dunes: a seasonal or sedentary option?

Settlement models have been proposed (e.g. Marchand 2001) in the framework of the hunter-gatherer economy of the Mesolithic groups in the Sado Valley. In general

lines, the site has been regarded as a semi-sedentary base-camp, articulated with Cabeço do Pez (see Fig. 10) in seasonal cycles (Arnaud 1989, 2000). These hypotheses are based on their larger size and the relative significance of lithic industries and faunal records at these sites in comparison with other sites in the Sado Valley. The identification of residential structures (e.g. post-holes and fireplaces), and ecological characteristics of the area, particularly the existence of a freshwater source, were considered the mainstays supporting these hypotheses (Larsson 1996; Arnaud 2000).

The micromorphological analysis of the shell midden layers at Poças de São Bento can contribute to the temporal characterisation of, at least, the sampled contexts. The microstratigraphic record points to a rapid formation process characterised by quick and short events of anthropogenically deposited sediments. A possible exception is that of the few upper centimetres of mF type 6a, *silty sands with few shells*, at the base of the shell midden. This is the only microfacies where the presence of shells is not clearly intentional but more likely explained by a combination of surficial rolling promoted by wind action over the already occupied dune and a non-intentional transport by humans (e.g. trampling).

Considering that aeolian processes might be active at the time of the shell midden formation and that there are topographically higher positions around the site, we can envision a very short time between each event in Area 9, at least, short enough to prevent natural wind-induced sedimentation to occur. The aforementioned indicators of rapid burial of mF type 5, *shell-supported sediments*, also point to this hypothesis. For these reasons, we argue for an accumulation of the vertical sequence in Area 9 during the same period of occupation, rather than the result of events belonging to occupations separated by large periods of total abandonment of the site.

Concerning Area 1, microfacies analysis also provided evidence of superimposed anthropogenic deposits. A deposit resulting from anthropogenic reworking was overlaid by an occupational surface affected by intense trampling. That surface was later covered by a new load of reworked debris, of short enough duration to prevent natural sedimentation occurring. For the same reason as for Area 9, we think that these events took place during the same “occupation”. At Cabeço da Amoreira, thin lenses of crudely bedded silt to fine sand were sometimes found overlying occupational surfaces, and then a new dumping event covered the lenses. This was used by the authors to argue for a temporary abandonment of, at least, that area of the site (Aldeias and Bicho 2016), which cannot be stated for the current sedimentary record of Poças de São Bento.

Overall, there are not enough data to distinguish sedimentologically different occupations in the vertical stratification at Poças de São Bento during the Mesolithic. One possible way

to solve this question would be through isotopic analysis of the shells in order to establish seasonality patterns integrated with the microstratigraphic evidence for different episodes of shell accumulation while sampling.

Conclusions

The present study provided significant results for research on Mesolithic societies at Poças de São Bento, particularly regarding interpretation of the archaeological record. Concerning site-specific research questions, one of the most interesting outcomes of the micromorphological approach is that there *was* intentional superposition of shell-rich sediments, and not only lateral juxtaposition of anthropogenic deposits, as systematically assumed in previous studies on the Sado shell middens. Our approach revealed the distinction between dumped sediments and occupational surfaces within the shell midden layer at Area 1. This layer is actually macroscopically equivalent to most of the shell-rich deposits in all the excavated areas at the site, and very often the only one. Our analysis suggests a full internal dynamic in the formation of this apparently homogeneous shell midden layer. This evidence points to the need for further micromorphological approaches in similar deposits in other areas of the site, especially the pit infillings, in order to track the areas and activities complementary to those inferred microscopically.

At a broader, Sado Valley scale, the remarkable occurrence of elements such as clay aggregates and foraminifera in anthropogenically reworked sediments most probably indicate transport of marshland components directly from the gathering place to the site, as a consequence of shellfish gathering techniques. Calcareous pebbles in the same sediments, when related to the regional geology, provide sedimentological evidence suggesting that the shellfish gathering was not carried out in the vicinity of the site, but ~8–12 km downstream. These aspects have major implications regarding future studies of logistical movements of the Mesolithic hunter-gatherers in the valley, and also the pending question of the extension of the palaeo-estuary during that period.

From macroscopically visible stratified accumulations, such as at Area 9, we were able to recognise human actions such as preferential discard of debris, single tossing events, and dumping of intentionally reworked sediments. The results show a lack of evidence of abandonment periods inside these deposits. This is an open question that could be investigated in the future. Particularly interesting for this issue are seasonality studies through isotopic analysis of the shells, based on the microstratigraphy of the different human-induced sedimentary events in order to

prevent inadvertent mixing of materials from different events in the sampling of archaeological materials.

Tossing of debris, sediment dumping and spreading out, trampling and preferential refuse areas are some of the activities, inferred from the microstratigraphic record that Poças de São Bento has in common with Cabeço da Amoreira. These similarities appear to be revealing the same anthropogenic patterns in the activities involved in the formation of both sites. These observations open new research possibilities for other similar contexts regarding more general behavioural dynamics. The study of shell midden formation processes, through microcontextual approaches, has played a major role in our knowledge of Mesolithic societies at the two largest early Holocene estuarine ecological settings of the central/south Portuguese coast.

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